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Energy Recovery in Wastewater Treatment Plants Through Micro Hydroelectric Systems: A Feasibility Assessment

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ABSTRACT

This study aims to evaluate the energy production potential of micro-hydroelectric power plant (M-HES) applications at the Batman Wastewater Treatment Plant (WWTP). The energy production potential was calculated by considering different flow types and hydraulic head heights. The results indicate that M-HES applications could provide an annual energy production of 142,939.5 kWh to 188,879.3 kWh, meeting approximately 15.06% to 19.89% of the plant's total energy consumption. The findings demonstrate that M-HES systems offer a viable solution not only for the Batman WWTP but also for other wastewater treatment plants with similar infrastructures, serving as a guide for future engineering projects.

1. Introduction

Wastewater treatment plants (WWTP) are fundamental infrastructure elements of modern societies, operating to protect water resources, ensure public health, and promote environmental sustainability. These facilities effectively treat domestic and industrial wastewater, contributing to both the preservation of ecosystems and the reuse of water resources. However, wastewater treatment processes often require significant energy consumption. This energy demand constitutes a substantial portion of operational costs and, due to greenhouse gas emissions generated during energy production, poses challenges to achieving environmental sustainability goals. Therefore, developing strategies to improve the energy efficiency of wastewater treatment plants has become a critical necessity to reduce economic costs and minimize environmental impacts.

Water and energy are two critical resources for the sustainability of modern societies, offering significant opportunities for environmental protection and economic benefits through their integrated management. Traditionally, water supply and energy production systems have been designed independently, yet there exists a strong interdependence known as the “Water-Energy Nexus” [1,2]. While energy production requires water for processes such as cooling and steam generation, the collection, treatment, and distribution of water are energy-intensive activities. This interrelation underscores the critical importance of integrated management of water and energy systems in reducing costs, lowering greenhouse gas emissions, and ensuring the sustainable use of resources. In particular, energy efficiency applications in water and wastewater treatment plants hold great potential for improving economic performance and contributing to environmental sustainability. Innovative technologies and strategies play a pivotal role in achieving these objectives and are essential for meeting the United Nations' 2030 Sustainable Development Goals.

The water sector faces multifaceted challenges, including the adverse impacts of climate change on water resource availability, rapid population growth, industrialization, and infrastructural issues. Climate change introduces unpredictable shifts in water regimes, threatening both water supply and quality, while population growth and industrialization place increasing pressure on existing resources. These pressures are further compounded by operational issues such as aging infrastructure, leaks, and deteriorating water quality. Additionally, rising energy costs present another critical challenge, as water provision and usage often involve energy-intensive processes. These factors not only increase the financial burden on the sector but also complicate efforts to achieve sustainability goals [3,4]. Addressing these issues requires integrated and innovative strategies to balance resource demands, ensure water security, and align with broader environmental and economic objectives.

Furthermore, the lack of effective coordination among stakeholders such as water authorities, regulators, and political entities exacerbates pressing socio-economic, environmental, and resilience challenges in water management. Addressing these issues requires holistic approaches that encompass efficient resource management, modernization of infrastructure, and enhanced collaboration among stakeholders. Such strategies are not only essential for ensuring the sustainability of the water sector but also hold significant potential to contribute to societal well-being and environmental protection. By fostering integrated and cooperative efforts, these approaches can help mitigate current challenges and align water management practices with long-term sustainability goals.

To enhance energy production and efficiency in wastewater treatment plants, modifications involving the integration of renewable energy sources, alongside methane production, offer significant potential. Incorporating renewable energy systems such as solar and wind power provides sustainable and environmentally friendly solutions to meet the energy demands of these facilities. For instance, photovoltaic panels installed within the facility premises can generate electricity from solar energy, while wind turbines can be utilized in suitable areas around the plant to harness wind energy effectively. Additionally, micro-hydroelectric power systems (M-HES) represent an innovative modification, particularly suited for low-flow and low-head conditions at water flow points or discharge outlets of the treatment plants. These solutions not only diversify the energy portfolio of wastewater treatment facilities but also contribute to reducing their carbon footprint and operational costs, aligning with broader sustainability objectives.

Hydroelectric systems are renewable energy technologies that generate electricity by utilizing the flow of water to drive turbines. A subtype of these systems, M-HES, stands out as an innovative and sustainable energy source [5,6]. One of the most significant advantages of M-HES is that they do not require the construction of large dams or reservoirs, as is the case with large-scale hydroelectric systems, thereby minimizing environmental impacts. Recognized as an environmentally friendly alternative in renewable energy production, M-HES systems are particularly suited for water sources with low flow rates and low hydraulic head differences. Their adaptability and minimal ecological footprint make them a viable option for sustainable energy solutions, especially in regions where traditional hydroelectric systems may not be feasible.

The applicability of M-HES for energy production in wastewater treatment plants has been evaluated in various studies. Erkan et al. [7] conducted theoretical calculations based on the hydraulic head differences between the outlet and discharge points at the Van-Edremit, Elâzığ-Sivrice, and Tunceli central treatment plants, determining energy recovery rates of 20%, 9.5%, and 6.6%, respectively. Baran

[8] highlighted that the Marmara Region has the highest electricity generation potential, whereas the Eastern Anatolia Region has the lowest. The study also predicted a significant increase of up to 138.58% in the Black Sea Region's energy production potential due to rising flow rates between 2018 and 2025. Kayıkçı et al. [9] analyzed the energy production potential in three different wastewater treatment plants in Istanbul, leveraging hydraulic head differences between units. Their findings indicated that M-HES systems could achieve up to 10% energy savings with payback periods ranging from 0.5 to 0.9 years. The turbine power potentials were calculated as 93.34 kW/h, 90.21 kW/h, and 36.85 kW/h. These studies collectively demonstrate that M-HES offers an environmentally friendly and economically viable energy solution, with significant potential for integration into wastewater treatment systems.

This study examines the feasibility and energy recovery potential of micro-hydroelectric power plants (M-HES) in the Batman Wastewater Treatment Plant (WWTP). The analysis evaluates the impacts of M-HES design models on energy production, energy efficiency, and the plant’s annual energy consumption. Based on the plant’s current potential, the contribution of energy recovery to the facility’s energy consumption and the resulting economic savings were analyzed. These findings have been compared with the results of similar studies in the literature to provide a comprehensive evaluation..

2. Material and Method

2.1 Study Area

In the city center of Batman, a wastewater treatment plant (WWTP) operated by the Batman Municipality serves the region. The Batman Municipality WWTP processes approximately 61,000 m³ of wastewater daily through physical treatment methods before discharging it into the Batman River. Although the facility does not include biological or advanced treatment processes, it provides physical treatment capacity for an area of 85 km², serving a population of approximately 477,456 [10]. The location of the WWTP, along with the Batman River and its basin, is shown in Figure 1. Daily wastewater inflow data for the Batman WWTP have been analyzed for the years 2011–2022 (excluding 2018). To estimate potential flow rates, the average daily wastewater values were categorized into rainy and dry periods for each calendar year. The average flow values for the plant are presented in Table 1.

Figure 1. Study area

Within the scope of this study, the geographical, demographic, and technical characteristics of the Batman Municipality WWTP were analyzed to assess its potential for energy efficiency and the integration of renewable energy sources. The data obtained from the facility aim to contribute to the development of sustainable approaches to wastewater management in the region.

Table 1. Wastewater inlet flows for Batman WWTP (m^3/d)

Year	***ADF***[a]	***MDF***[b]	***ADDF***[c]	***MDDF***[d]	***ADRF***[e]	***MADRF***[f]
2011	46.556	73.352	46.291	66.244	49.154	73.552
2012	46.404	75.778	46.323	61.542	46.660	75.778
2013	49.767	63.465	50.041	63.465	48.342	63.099
2014	47.544	63.043	47.745	63.043	46.683	54.099
2015	53.130	63.372	54.040	63.372	49.999	60.952
2016	49.631	62.094	49.641	60.442	49.571	62.094
2017	49.922	61.609	49.686	61.609	51.021	60.904
2019	53.543	61.708	53.614	61.708	53.256	61.151
2020	56.198	62.187	56.769	62.187	53.870	61.566
2021	41.368	61.132	40.920	61.132	44.704	61.105
2022	33.149	48.566	33.000	48.566	33.694	46.767
Average	47.93	63.30	48.01	61.21	47.90	61.92

[a]Average daily wastewater flow
[b]Maximum daily wastewater flow
[c]Average daily dry wastewater flow
[d]Maximum daily dry wastewater flow
[e]Average daily rainy wastewater flow
[f]Maximum daily rainy wastewater flow

2.2 Energy Recovery in Wastewater Treatment Plants: M-HES

Energy recovery in wastewater treatment plants (WWTPs) holds significant potential for both environmental sustainability and economic savings. Optimizing the energy-intensive processes involved in water treatment and integrating renewable energy systems reduce energy consumption and minimize the carbon footprint. Innovative applications, such as micro-hydroelectric power plants (M-HES), enable energy recovery by harnessing the movement of wastewater.

In WWTPs, treated wastewater can be utilized for electricity generation in M-HES before being discharged into receiving environments after disinfection. M-HES provides an environmentally friendly, reliable, and stable alternative for renewable energy production in wastewater treatment plants. These systems are particularly advantageous due to their minimal environmental impact and ability to operate without requiring dam construction, large land areas, or causing significant ecological disruption. The energy production potential of treated wastewater can be calculated by considering flow fluctuations during summer and winter seasons as well as day and night cycles. Power output can also be estimated based on varying flow rates and hydraulic head heights. The use of impulse turbines, in particular, enhances flow velocity, increases the dissolved oxygen concentration in the discharge water, and positively impacts water quality [11,12]. Thus, M-HES applications play a dual role by not only contributing to renewable energy generation but also improving water quality, demonstrating their critical importance in the sustainable management of wastewater treatment facilities.

Hydroelectric power plants convert the potential energy of water into electricity, with production capacities ranging from a few kilowatts to thousands of megawatts. These systems are highly versatile and can be implemented in any location with sufficient flowing water, from small-scale applications to large infrastructure projects. Micro-hydroelectric power plants (M-HES) refer to plants with a production capacity of less than 100 kW, standing out as cost-effective and environmentally friendly energy solutions [13]. If a WWTP has suitable hydraulic head and flow conditions, renewable energy production can be achieved using M-HES technology. However, several key criteria must be considered for such investments:

- **Treated wastewater flow rate**: The continuity of adequate flow is critical for energy production.
- **Hydraulic head height**: The elevation difference is a decisive parameter affecting energy conversion efficiency.
- **Turbine type**: Selecting the most appropriate turbine for the specific flow rate and head height is essential.
- **Investment cost**: Initial installation costs, payback periods, and long-term economic benefits should be evaluated.
- **Electricity price**: Regional energy prices significantly influence the investment's return on investment (ROI).

When these parameters are carefully considered, the installation of M-HES in WWTPs offers an effective solution for both energy production and environmental sustainability, contributing to operational efficiency and reduced carbon emissions.

2.3 Design Approach for Micro HEPP

Micro-hydroelectric power plants (M-HES) are systems that do not require a reservoir, unlike large dams, and provide sustainable energy production with minimal environmental impact. In these systems, only a portion of the flowing water is utilized for energy production, and the system is typically installed between units within a wastewater treatment plant or between the plant's outlet and discharge point. To calculate the actual power output (P) in M-HES, factors such as friction losses in penstocks and turbine/generator efficiency must be considered. While modern turbine technologies can achieve efficiencies exceeding 90%, the overall system efficiency generally ranges from 60% to 80%, depending on the hydraulic head and flow rate.

The energy production in M-HES is determined using the following formula:

$$P = Q * H * g * \eta \tag{1}$$

Here;
P; Electrical energy power (kW)
Q; Wastewater flow rate (m^3/s)
H: Net hydraulic drop, (m)
g; Gravitational acceleration, 9.81, (m/s^2)
ρ: Density of treated wastewater (kg/m^3)
η; Efficiency of microturbine, (dimensionless)

This formula allows for the theoretical estimation of energy production potential, enabling the assessment of M-HES applicability in wastewater treatment plants, particularly for sites with suitable flow rates and head heights**.**

In this study, the flow rate data for the Batman WWTP were analyzed based on the categories outlined in Table 1. The flow rates were classified into average daily wastewater flow, maximum daily wastewater flow, average and maximum daily dry-season flow, and average and maximum daily rainy-season flow. Using a theoretical approach, the energy production potential for each flow rate was calculated using Equation 1. For these calculations, the density of treated wastewater was assumed to be 1000 kg/m^3, and the efficiency factor of the microturbine was taken as 0.75. The hydraulic head data for the M-HES were determined using Google Earth software, which identified the elevations at the plant's outlet and discharge points. Based on these findings, the hydraulic head for the proposed M-HES was assumed to be 4 meters. Analyses conducted under various flow scenarios allowed for an assessment of energy production capacity during both dry and rainy periods. This approach aimed to evaluate the system's performance under varying climatic and flow conditions and to optimize the energy recovery potential of the facility, contributing to the development of a more sustainable and efficient wastewater management system.

3. Results and Discussion

In this study conducted for the Batman Wastewater Treatment Plant (WWTP), the energy production potential of micro-hydroelectric power plant (M-HES) applications was evaluated using daily average flow rates. Based on calculations assuming a hydraulic head of 4 meters, the energy production potential for different flow types ranged between 16.31 kW and 21.56 kW (Table 2). These results align with similar studies in the literature [7-9], demonstrating that M-HES can make a significant contribution to renewable energy production in wastewater treatment plants.

Table 2. Potential for generating electrical energy for Batman WWTP

Flow ype	***ADF*[a]**	***MDF*[b]**	***ADDF*[c]**	***MDDF*[d]**	***ADRF*[e]**	***MADRF*[f]**
P (kW)	16.32	21.56	16.35	20.84	16.31	21.08
P(kWh/y)	143011.2	188879.3	143243.9	182643	142939.5	184746.6

Domestic water consumption and the resulting wastewater production tend to peak at specific times of the day, with these peak periods typically occurring during the early morning hours, prior to the start of the workday, and in the evening, following post-work activities. These fluctuations in wastewater production are influenced not only by the time of day but also by seasonal variations. During summer months, increased water usage driven by factors such as irrigation and cooling leads to higher peak values, whereas these values tend to decrease during the winter months. Such dynamics play a critical role in the energy consumption and capacity management of wastewater treatment plants. Therefore, it is essential to optimize system designs to accommodate these daily and seasonal variations, ensuring efficient and sustainable operation of the facilities.

The energy recovery rates were calculated by comparing the energy generated by the proposed M-HES with the energy consumption of the facility (Table 3). Based on the current flow and hydraulic head characteristics of the plant, the annual energy production capacity was determined to range between 142,939.5 kWh and 188,879.3 kWh (Table 2). When compared to the total energy consumption of 949,310 kWh in 2023, the M-HES applications could meet approximately 15.06% to 19.89% of the facility's energy needs. This contribution is significant for reducing energy consumption and enhancing environmental sustainability in energy-intensive wastewater treatment plants.The obtained results align with findings from the literature. For instance, Erkan et al. [7] reported energy recovery rates ranging from 6.6% to 20% in studies conducted on wastewater treatment plants in Van-Edremit, Elâzığ-Sivrice, and Tunceli. Similarly, Kayıkçı et al. [9] highlighted that M-HES systems in wastewater treatment plants in Istanbul could achieve energy savings of up to 10% with payback periods of 0.5 to 0.9 years. These findings demonstrate the significant potential of the Batman WWTP to contribute to energy efficiency and sustainability goals through the implementation of M-HES. By leveraging its existing flow and hydraulic head potential, the facility could play a vital role in advancing renewable energy integration and reducing its operational carbon footprint.

Table 3. Batman WWTP electricity consumption quantity

Date	T1 (07:00-18:00)	T2 (18:00-23:00)	T3 (23:00-07:00)	Active (kWh)
31/08/2023	36,421	17,157	27,543	81,122
04/09/2023	961	84	589	1,634
30/09/2023	2,020	1,030	1,687	4,736
31/10/2023	40,843	20,806	33,678	95,328
30/11/2023	16,669	8,921	14,673	40,263
31/12/2023	50,519	26,820	40,878	118,217
31/01/2024	13,921	6,991	11,389	32,300
29/02/2024	38,576	19,433	30,555	88,564
31/03/2024	46,638	23,979	38,502	109,119
30/04/2024	21,278	10,169	17,017	48,465
31/05/2024	42,245	20,399	33,446	96,091
30/06/2024	33,475	15,521	25,336	74,332
31/07/2024	16,276	7,669	12,675	36,619
31/08/2024	55,593	25,685	41,242	122,520
Total	**415,435**	**204,664**	**329,210**	**949,310**

The primary advantages of M-HES systems lie in their environmentally friendly design, low investment costs, and broad range of applications. The energy production values calculated in this study demonstrate that the implementation of M-HES at the Batman WWTP can significantly reduce the facility’s energy consumption while providing long-term economic benefits. However, advancing energy efficiency in wastewater treatment plants will require the development of more sophisticated engineering solutions and optimized designs. Such improvements will play a critical role in achieving regional energy goals. Furthermore, a detailed analysis of the effects of flow fluctuations during dry and rainy periods on energy production is essential to enhance the efficiency and effectiveness of these applications. Addressing these factors will ensure that M-HES systems not only meet energy demands but also contribute to broader sustainability objectives.

4. Conclusion

This study comprehensively evaluated the energy production potential of micro-hydroelectric power plant (M-HES) applications at the Batman Wastewater Treatment Plant (WWTP). The analyses revealed that M-HES systems could meet approximately 15.06% to 19.89% of the plant's annual energy consumption, which is 949,310 kWh. These results demonstrate the significant contribution of M-HES systems in enhancing energy efficiency and promoting the use of renewable energy sources in wastewater treatment plants.

The findings of this study are not only relevant for the Batman WWTP but also serve as a guide for other wastewater treatment facilities with similar infrastructures. Moving forward, it is recommended to optimize M-HES designs to accommodate flow fluctuations, select turbines to maximize efficiency, and conduct a more detailed analysis of seasonal variations.

In conclusion, M-HES applications have the potential to transform wastewater treatment plants from energy-consuming infrastructures into energy-generating systems, thereby contributing significantly to the development of sustainable energy policies and practices.

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