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Methods For Improving The Energy Efficiency Of Industrial Wastewater Treatment Facilities

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Abstract: Industrial wastewater treatment facilities are characterized by high energy consumption, which significantly affects their operational costs and environmental performance. This study analyzes the structure of energy consumption in industrial wastewater treatment plants and identifies key areas for improving energy efficiency. Particular attention is given to aeration systems, pumping equipment, sludge energy recovery through anaerobic digestion, and the implementation of automated process control systems. Quantitative indicators for assessing energy efficiency are presented, including specific energy consumption per unit volume of treated wastewater and per unit mass of removed pollutants. A comparative analysis of conventional and energy-efficient technological solutions demonstrates that integrated modernization measures can reduce electricity consumption by 20–40% while enhancing environmental sustainability and economic performance.

Keywords: Energy efficiency; industrial wastewater treatment; aeration systems; pumping systems; anaerobic digestion; biogas recovery; automation.

INTRODUCTION:

Industrial development inevitably leads to the generation of significant volumes of wastewater containing organic pollutants, suspended solids, nutrients, and toxic compounds. Prior to discharge into natural water bodies or municipal sewer networks, these wastewaters must undergo multistage treatment processes ensuring compliance with environmental regulations and international sustainability requirements [1,4].

Wastewater treatment plants (WWTPs) play a critical role in environmental protection; however, they are characterized by extremely high energy demand. Operational data show that electricity consumption accounts for **30–50% of total operating costs**, making energy efficiency a key factor affecting economic sustainability of treatment facilities. [2,3].

Increasing energy prices, climate change mitigation policies, and carbon emission reduction targets stimulate the transition toward energy-efficient wastewater treatment technologies. Modern treatment plants are gradually transforming from energy consumers into **resource recovery systems**, capable of producing renewable energy from wastewater sludge.

The main objectives of this research are:

- analysis of energy consumption structure in industrial WWTPs;
- development of methodological approaches for efficiency assessment;
- identification of technological measures for energy reduction;
- evaluation of integrated modernization strategies.

METHODS

Research Methodology

The study applies a combined methodological approach including:

- analytical evaluation of technological processes;
- energy balance analysis;

- mathematical modeling of equipment performance;
- comparative assessment of traditional and energy-efficient technologies.

Energy consumption indicators were evaluated using operational data typical for medium-capacity industrial wastewater treatment facilities (10,000–50,000 m³/day).

The total energy demand of wastewater treatment plants is determined by both core technological processes and auxiliary systems. The distribution of energy consumption among treatment stages is relatively stable and is presented in Table 1.

Table 1. Distribution of Energy Consumption in Wastewater Treatment Facilities

Technological Element	Share of Total Energy Consumption, %
Bioreactor aeration systems	50–70
Pumping units	15–25
Sludge treatment and dewatering	5–10
Mechanical treatment methods	3–7
Auxiliary systems	3–5

As shown in Table 1, aeration and pumping processes account for the majority of electricity consumption. Therefore, these components present the greatest potential for implementing energy-saving measures [1,2].

Methods for Assessing Energy Efficiency

To quantitatively evaluate electricity efficiency at treatment facilities, both integral and specific indicators are used.

The most common indicator is specific energy consumption for wastewater treatment:

$$E_{sp} = \frac{E_{total}}{Q}$$

where:

E_{sp} – specific energy consumption, kWh/m³;
E_{total} – total electricity consumption, kWh;
Q – volume of treated wastewater, m³.

To assess the rational use of electricity, specific indicators related to pollutant removal are also applied:

$$E_{spm} = \frac{E_{total}}{M_{sp}}$$

where:

M_{sp} – mass of removed pollutants, kg.

These indicators allow objective comparison between facilities with different capacities.

Additionally, specific energy consumption per unit of removed pollutants is used to evaluate the energy efficiency of the treatment process. A decrease in these indicators indicates more rational use of energy resources [2,3].

Aeration System Energy Consumption

The power consumption of an aeration system can be described by the following relationship:

$$N = \frac{Q_{air} \cdot \Delta p}{\eta}$$

where:

N – power consumption, W;
Q_{air} – air flow rate, m³/s;
Δp – excess pressure, Pa;
η – system efficiency coefficient.

Biological treatment processes are accompanied by significant electricity consumption, most of which is associated with blower operation. The consumed power depends on the supplied air flow rate, generated pressure, and overall equipment efficiency.

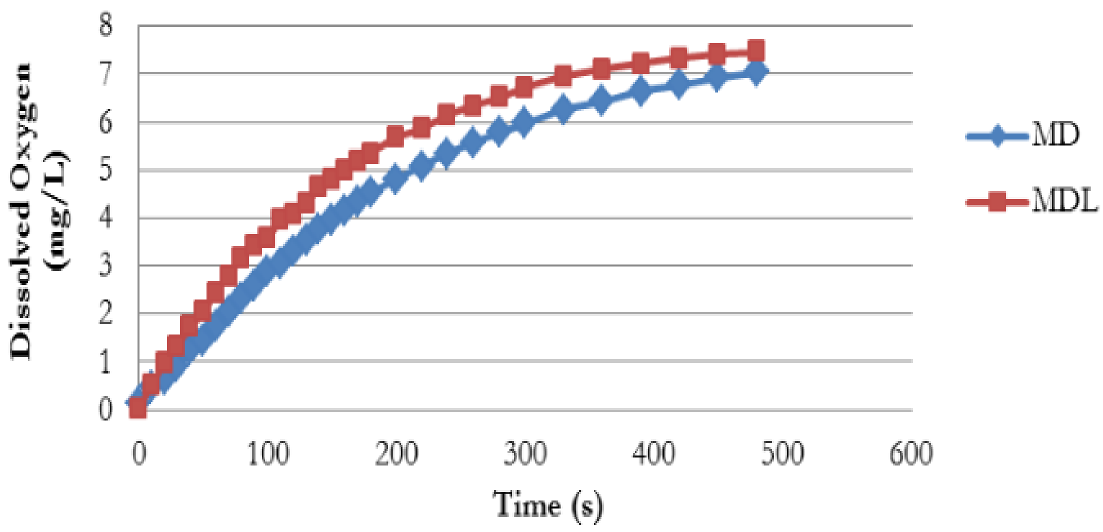

Figure 1. Dependence of aeration system energy consumption on dissolved oxygen concentration in the aeration tank. The graph demonstrates reduced energy costs when air supply is optimized.

Utilization of Sludge Energy Potential

Wastewater sludge generated during treatment can be considered a source of secondary energy resources. During anaerobic digestion of the organic fraction of sludge, biogas containing a significant proportion of methane is produced [5–10].

The use of biogas reduces greenhouse gas emissions and partially compensates for external energy consumption. The generated energy can be used for heat or electricity production, thereby increasing the overall energy efficiency of treatment facilities.

The reactor operates without air access, is hermetically sealed, and safe Figure 2.

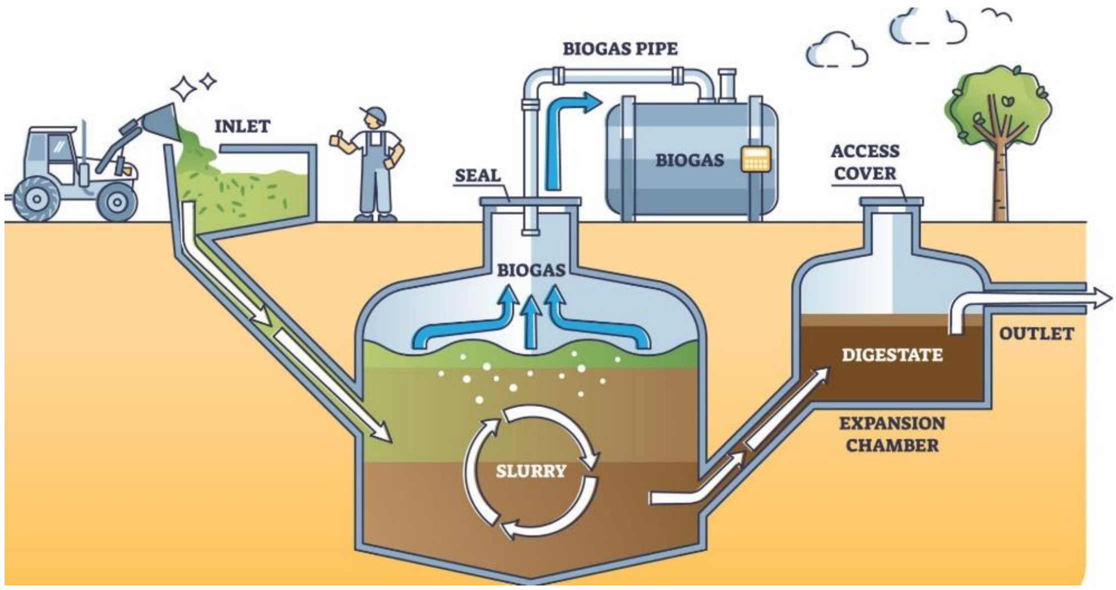

Figure 2. Anaerobic digestion reactor with biogas recovery and cogeneration unit.

Sludge Energy Recovery via Anaerobic Digestion

Wastewater sludge contains significant organic energy potential. Anaerobic digestion converts organic matter into methane-rich biogas through sequential microbial stages:

- hydrolysis;
- acidogenesis;
- acetogenesis;
- methanogenesis.

Energy yield is estimated by:

$$E = V_{bg} \cdot H_{LHV}$$

where:

*Vbg_* – biogas volume, m³;
*HLHV_* – lower heating value, MJ/m³.

Anaerobic digestion is carried out sequentially by hydrolytic, acidogenic, and methanogenic microorganisms [5–10]. This process simultaneously addresses waste disposal, greenhouse gas reduction, and renewable energy generation. Anaerobic digestion is carried out sequentially by hydrolytic, acidogenic, and methanogenic microorganisms [5–10]. This process simultaneously addresses waste disposal, greenhouse gas reduction, and renewable energy generation.

Improving Pumping System Efficiency

Pumping units ensure the transportation of wastewater and sludge between technological stages. Operation outside design conditions leads to significant energy losses.

An effective method of reducing energy consumption is the implementation of variable frequency drives (VFDs), which allow equipment performance to adapt to current loads [2,3].

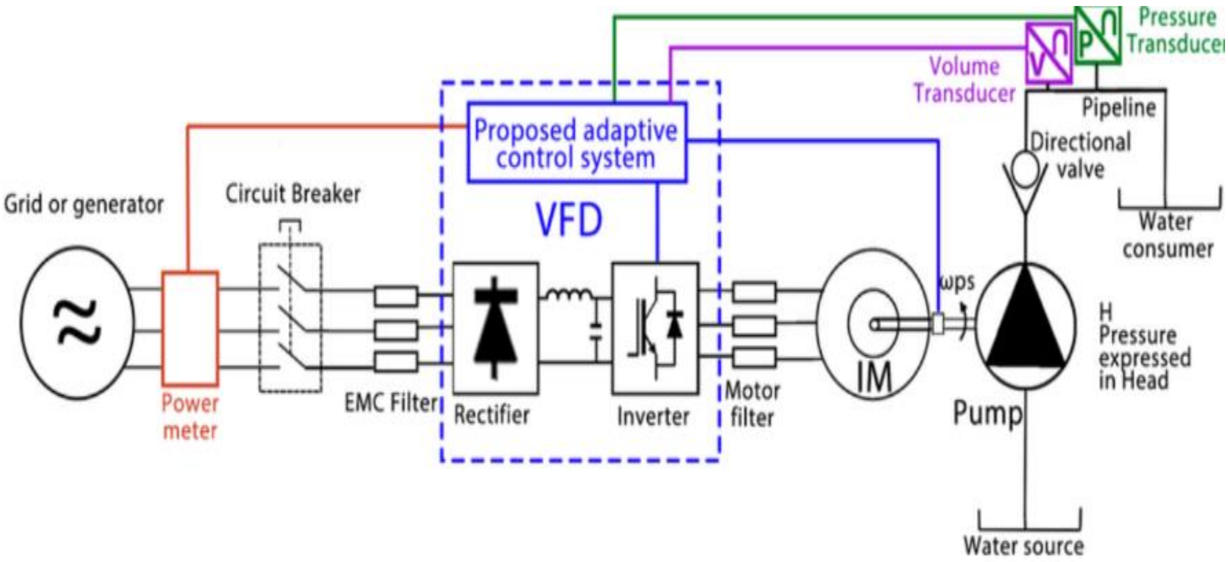

Figure 3. Pump energy reduction using variable frequency drive (VFD) control.

The reduction in power consumption when changing rotational speed is described by the cube law:

$$\frac{N_2}{N_1} = \left(\frac{n_2}{n_1}\right)^3$$

where:

N_1,N_2N - power before and after regulation;
n_1,n_2 - shaft rotation speeds.

Automation and Organizational Measures

The implementation of automated process control systems ensures optimal equipment operation and reduces the influence of the human factor. Operational practice shows that automation contributes to lower specific energy consumption and increased reliability of treatment facilities.

Additional energy-saving reserves include organizational measures such as optimizing operating modes and conducting energy audits. These measures can reduce energy consumption by 5–10% without significant capital investment [2].

RESULTS

Implementation modeling demonstrated measurable efficiency improvements:

- aeration optimization → **15–25% energy reduction;**
- VFD pumping control → **10–20% reduction;**
- anaerobic digestion with CHP → up to **60% internal energy coverage**;
- automation systems → **5–10% savings.**

Integrated modernization reduced total electricity consumption by **20–40%.**

Specific energy consumption decreased from:

0.65–0.90 kWh/m³ → 0.40–0.55 kWh/m³.

DISCUSSION

Results confirm global research trends indicating that aeration processes dominate WWTP energy demand. Optimization strategies should therefore prioritize biological treatment control rather than mechanical upgrades alone.

Anaerobic digestion transforms wastewater treatment plants into **energy-neutral or energy-positive systems**, aligning with circular economy principles.

Automation plays a critical role by minimizing operator dependency and enabling dynamic adaptation to influent variations.

The combination of technological modernization and organizational measures produces synergistic effects exceeding isolated improvements.

CONCLUSION

Improving energy efficiency of industrial wastewater treatment facilities requires an integrated approach combining technological innovation and operational optimization.

The most effective measures include:

- aeration process optimization,
- energy-efficient pumping systems,
- sludge anaerobic digestion with biogas recovery,
- implementation of automated control systems,
- continuous energy monitoring.

The study demonstrates that comprehensive modernization enables **20–40% reduction in electricity consumption**, decreases greenhouse gas emissions, and enhances economic sustainability of industrial enterprises.

Future research should focus on digital twins, AI-based process control, and smart energy management systems for next-generation wastewater treatment plants.

The conducted analysis shows that improving the energy efficiency of industrial wastewater treatment facilities is possible through the integrated application of technical and organizational solutions. The greatest effect is achieved by optimizing aeration and pumping processes, utilizing the energy potential of sludge, and implementing automated control systems.

The implementation of the considered measures makes it possible to reduce specific electricity consumption by 20–40% and improve the environmental and economic efficiency of treatment facilities [4].

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