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Research Article

Improving The Energy Efficiency Of Wastewater Treatment Facilities During Reconstruction

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ABSTRACT

The present work provides a structured examination of approaches for improving the energy efficiency of municipal and industrial wastewater treatment plants (WWTPs) under conditions of deep reconstruction. Against the backdrop of pronounced volatility in energy markets in 2022–2023—when EU electricity prices reached record levels in the first half of 2023—the reduction of operating expenditures became a priority engineering and economic objective. Within the study framework, a benchmarking methodology based on specific indicators (kWh/m^3 , $\text{kWh}/\text{kgCOD}_{rem}$) is considered; a comparative analysis of technological solutions for CAS and MBR configurations is carried out; and the attainability of partial energy self-sufficiency through biogas cogeneration is assessed. Scientific novelty is associated with the development of an integrated model for selecting a modernization strategy that accounts for equipment performance, operational constraints, and the digitalization potential embedded in the “water sector digital transformation / Water 4.0” logic. The results indicate that advanced control (including AI/ML-based decision support where data quality allows) and modern membrane technologies can enable a 20–30% reduction in energy consumption while maintaining compliance with stringent environmental requirements. The material is oriented toward chief engineers of design organizations, specialists of utility operating services, and developers of environmental protection equipment.

KEYWORDS

energy efficiency, wastewater treatment plant reconstruction, membrane bioreactor, specific energy consumption, biogas, aeration, digital twin, environmental standards, sewerage.

INTRODUCTION

The current stage in the evolution of sewerage and wastewater treatment systems is shaped by a compound challenge: the need to raise effluent treatment quality while simultaneously achieving a substantial reduction in operating expenditures, within which the share of electricity costs can reach 30–40% [1]. In 2022–2023, a sharp increase in electricity prices was recorded in the EU, with the first half of 2023 showing peak values in Eurostat statistics; this materially increases the sensitivity of WWTP OPEX to aeration and pumping regimes [1]. In parallel, the market for wastewater treatment equipment and services continued to expand in 2023, reflecting stable investment demand despite macroeconomic turbulence [2].

The purpose consists in substantiating and formalizing a strategy for energy-efficient reconstruction of municipal and industrial wastewater treatment plants through benchmarking of specific energy consumption, comparison of technological configurations (CAS/MBR), and assessment of energy self-sufficiency enabled by biogas recovery and the digitalization of process control.

The author's hypothesis is based on the assumption that achieving energy neutrality of wastewater treatment plants is, in principle, feasible only when deep modernization of aeration (including variable-frequency drives and optimization of oxygen mass transfer) is combined with the most complete possible utilization of the energy potential of biomass (biogas/cogeneration) and the deployment of AI-enabled and digital models for predictive mode control.

The scientific novelty of the work is supported by the formation of an integrated model for selecting a reconstruction strategy, grounded in correlational relationships between dynamic parameters of oxygen mass transfer and the facility's energy self-sufficiency potential, attained through advanced sludge processing.

Reconstruction under contemporary conditions is interpreted not as a local replacement of physically worn units, but as a systemic retuning of the technological cycle, including a reassessment of hydraulic, aerobic, and energy circuits. In the practice of LLC "Istekoil," which has implemented large projects since 1991, reconstruction solutions are regularly associated with adapting inherited Soviet-era capacities to current sanitary-environmental and resource constraints [3]. Within the 2022–2023 agenda, technologies that reduce the need for capital construction through process intensification tend to dominate; among them is the shift toward membrane filtration, capable of delivering a twofold increase in capacity within the previous footprint of the tank farm [5]. At the same time, membrane-based schemes require a stringent energy-balance assessment, because membrane aeration used to prevent fouling can increase total energy consumption by 60% or more [5]. In this context, the systematization of global trends includes the concept of "Water Treatment 4.0," the application of artificial intelligence for predictive control, and the institutionalization of the circular economy, within which wastewater treatment plants are treated as infrastructure complexes for resource recovery - treated water, energy, and biogenic elements [2, 9]. Criteria for energy optimization are

refined through linking oxygen mass transfer parameters with digital predictive control models, while the working hypothesis presumes that energy neutrality is attainable only through a combination of deep aeration-system modernization, implementation of variable-frequency drives, and maximally complete utilization of the energy potential of biomass.

With regard to practical significance, the results of the work are applicable to U.S. utilities and industrial wastewater treatment facilities as an engineering and economic basis for modernization programs: they make it possible, via KPI benchmarking (kWh/m^3 , $kWh/kgCOD_{rem}$), to identify nodes of maximum losses (aeration/pumping) and to select reconstruction solutions (including CAS→MBR) with a predictable reduction in energy consumption on the order of 20–30% while maintaining discharge quality requirements. In addition, the proposed energy recovery loop (anaerobic digestion of sludge + CHP) and digital control (SCADA/AI/“digital twin”) support U.S. objectives related to improving the resilience of critical infrastructure, reducing OPEX and carbon footprint, and adapting to electricity price volatility and peak loads.

At the same time, the transferability of the conclusions is constrained by the fact that energy efficiency and payback (especially for MBR and cogeneration) depend strongly on the local tariff profile and the carbon intensity of electricity, the actual loading and composition of influent wastewater, the quality of instrumentation and metering, and the facility’s level of digital maturity; therefore, without calibration to data from a specific plant (SCADA/energy audit), resulting estimates may shift materially.

Materials and Methods

The methodological framework of the study was constructed on the basis of a systems approach to wastewater treatment plant life-cycle assessment and is oriented toward improving the reproducibility of results. Comparative benchmarking grounded in key performance indicators (KPIs) was applied as the central analytical instrument, including specific energy consumption per unit of treated volume (ECI_{m^3})

and per unit of removed pollutant load (ECI_{COD}). The application of the indicated metrics ensured normalization of the baseline data for facilities of differing capacities and thereby enabled a technically correct comparison of process configurations, effectively neutralizing the influence of scale as a confounding factor.

A quantitative appraisal of aeration processes was performed using mathematical modeling methods based on calculations of standard oxygen transfer efficiency (SOTE) and standard aeration efficiency (SAE) [19, 20]. Determination of the mass-transfer coefficient was conducted with the inclusion of correction factors (α , β , θ) that reflect the divergence of real-wastewater characteristics from the conditions conventionally adopted for clean water; this point is not cosmetic, but rather foundational for a valid interpretation of the energy performance of aeration systems under operational regimes [11, 12, 19].

The energy component of the reconstruction solutions was complemented by an energy-consumption audit and an analysis of the resource potential of biogas [16, 18]. To compute the theoretical methane yield from waste activated sludge, stoichiometric relationships (Boyle’s equation) were applied, which provided a reasoned basis for introducing combined heat and power (CHP) units as an element of a strategy aimed at improving energy



self-sufficiency during modernization [13, 21].

The empirical and bibliographic base was assembled from data reported in peer-reviewed Scopus/WoS publications (including outlets such as MDPI, Sustainability, and Energies) [1, 5, 21], as well as materials from international agencies (IEA, Eurostat). The computational-analytical block was oriented toward identifying the most vulnerable points within prevailing technological schemes and toward an evidence-based substantiation of the feasibility of transitioning to membrane-based solutions [5, 10].

To ensure applied validity, information extracted from SCADA systems at operating facilities was used, which made it possible to form a representative picture of energy consumption before and after modernization. This coupling of model-based calculations with operational data reduced the influence of systematic errors typical of purely theoretical assessments and supported the formation of a verified factual base that can be used in design practice and in the selection of engineering solutions.

Results and Discussion

Table 1. Dynamics of the global market and WWTP cost structure (compiled by the author based on [2, 17, 21])

Indicator	2022	2023	Trend	Indicator
Market context (equipment/services)	growth	growth	steady expansion	Market context (equipment/services)
Share of energy in OPEX (%)	30–35%	35–40%	↑ under high tariffs	Share of energy in OPEX (%)
Electricity price (EU, household; excl. taxes, average)	rising	peak (H1 2023)	↑ vs. pre-2021	Electricity price (EU, household; excl. taxes, average)
Share of digital solutions in reconstruction	increasing	increasing	↑ (SCADA, analytic)	Share of digital solutions in reconstruction

The global market for wastewater treatment technologies and services by the early 2020s has been increasingly discussed. On the one hand, investment inflows into resilient municipal infrastructure continue to intensify, including projects implemented through public-private partnership (PPP) formats. On the other hand, the cost of debt financing and technological equipment has been rising in a noticeable way, driven by trade restrictions and tariff measures; during 2022–2023, these conditions contributed to higher prices for turbine equipment, transformers, and membrane complexes [2].

According to available estimates, market volume may reach USD 173.31 billion by 2029 [2]. Among the key drivers of technological development are decentralized modular solutions that allow capacity to be scaled in step with changing water-management loads, as well as the digitalization of operational control and monitoring - often framed under the umbrella term “Wastewater Treatment 4.0” [2, 17]. Table 1 summarizes the main indicators of market dynamics and shifts in the expenditure structure.

A material role in investment decision-making is played by legal mechanisms that allocate risks and responsibilities between the public authority and the private partner. For sewerage and wastewater infrastructure, long payback horizons are typical, which in practice necessitates carefully drafted provisions on tariff regulation, indexation of user charges, the availability of budgetary commitments, and guarantees of service continuity for the population. Under conditions of escalating equipment costs, contractual clauses governing the redistribution of price risks become more consequential, including permissible grounds for price adjustments and delivery schedule changes, as well as requirements related to product origin and localization within public procurement.

A separate driver of market transformation is the tightening of environmental requirements for treatment performance and for the control of pollutants, including difficult-to-remove micropollutants. Regulatory practice across jurisdictions is shifting away from an exclusive focus on traditional indicators (biochemical oxygen demand, nitrogen, phosphorus) toward integrated monitoring, reporting, and discharge-liability regimes, which structurally increases demand for more complex process configurations and automated control systems [7]. This, in turn, reshapes the composition of capital and operating expenditures, elevating the importance of energy efficiency, sludge management, and the minimization of secondary emissions.

In addition, legal regimes governing the reuse of treated wastewater and the handling of resources recovered during treatment (process water for technical needs, nutrients, biogas) have been developing at a visible pace. The expansion of water reuse practices requires formalization of sanitary and

epidemiological criteria, quality regulations, permitting procedures, and operator liability when established parameters are not met. At the level of contractual architecture, the significance of clauses on guaranteed effluent quality, data verification, and the allocation of responsibility among the technology provider, the operating organization, and the asset owner tends to increase as reuse schemes move from pilot status to routine practice.

For LLC “Istekoil,” these trends imply the need to shift emphasis from predominantly technological characteristics toward economically grounded cost management in sewerage and wastewater treatment. Growth in tariff pressure and higher energy prices objectively increase the investment attractiveness of measures aimed at reducing electricity consumption, because the simple payback period becomes shorter under comparable capital expenditures and unchanged effluent-quality requirements. In such circumstances, priority is assigned not so much to expanding the number of technological stages, but to achieving the required performance at the minimum total cost of ownership of equipment and infrastructure. The distribution of electricity use across the main process units typically remains relatively stable in qualitative terms, whereas specific indicators vary substantially as a function of plant capacity. Economies of scale are expressed through lower unit costs as capacity and loading increase, reflecting both more efficient utilization of blowers and pumping equipment and the feasibility of introducing automated regime control without a disproportionate escalation of operating expenditures.

From a practical standpoint, an energy-saving program is reasonably formed on the basis of a legally sound energy assessment and reliable instrumented metering, allowing separation of the influence of

process regimes, influent wastewater quality, and actual facility loading. The absence of an adequate methodology for measuring and confirming achieved savings leads to disputable calculations, complicates the defense of investment decisions, and increases the risk that incurred costs will later be deemed economically unjustified under tariff review or audit procedures.

When selecting an organizational and legal model for implementing measures, a significant potential is associated with the use of energy service mechanisms, within which contractor remuneration is linked to a verified reduction in energy-resource consumption. To minimize legal risks, the contractual structure typically requires fixing the baseline level of consumption, defining normalization rules (including seasonality and fluctuations in wastewater composition), establishing verification procedures, allocating party responsibilities for data access, and specifying recalculation rules in the event of changes in operating

modes or subsequent modernization of the facility [4, 14].

It should also be taken into account that a transition toward more complex treatment schemes and the implementation of digital control systems inevitably raise requirements for cybersecurity and for the integrity of process data, as well as for the allocation of responsibility for fault tolerance and continuity of service provision. Documentation is therefore justified in fixing requirements for equipment compatibility, warranty obligations, the availability of service support, and the assured supply of critical spare parts, since precisely these factors - under price volatility and supply constraints - have a direct impact on the structure of operating expenditures and the stability of the production process.

For clarity, Figure 1 illustrates a typical distribution of energy consumption within a wastewater treatment plant.

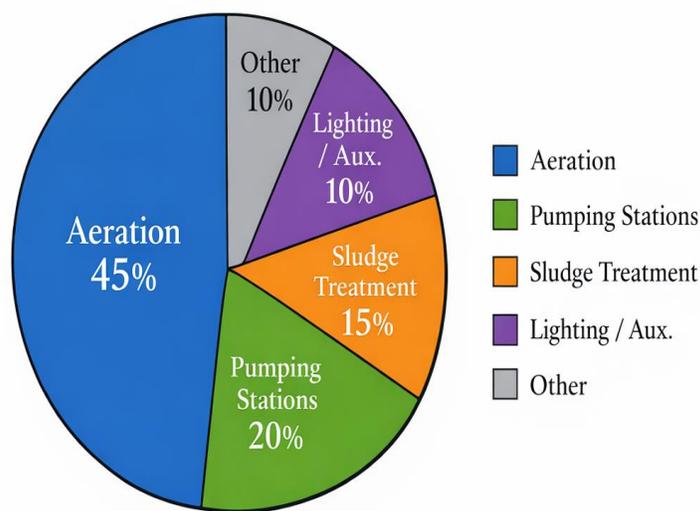


Fig.1. Typical distribution of energy consumption at a WWTP (compiled by the author based on [1, 10, 18]).

The data presented in Figure 1 indicate that optimization of aeration systems is, in a regular and

predictable manner, regarded as the most suitable lever for improving the energy efficiency of

wastewater treatment plants [19, 20]. At the same time, reconstruction planning must account for the “scale effect” as a matter of principle: for small facilities (up to 10,000 PE), structurally higher specific values are typical when compared with large plants, and even more so with mega-capacity installations,

because a fixed share of unavoidable energy use and limited opportunities for process intensification exert a much stronger influence on normalized indicators.

The dependence of specific energy consumption on plant capacity is illustrated in Figure 2.

Economies of scale: kWh/m³ versus capacity (PE)

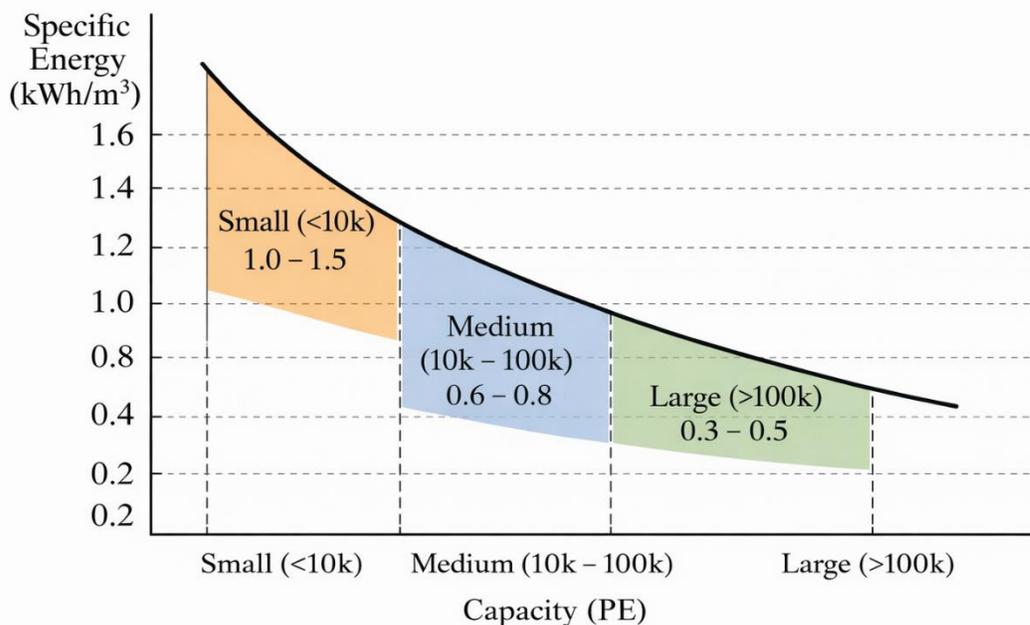


Fig.2. Relationship between specific energy consumption and plant capacity (compiled by the author based on [1]).

Table 2 consolidates comparable characteristics of different aeration technologies applied in wastewater treatment plant reconstruction, which allows their energy performance and operational feasibility to be

assessed in a technically consistent manner when selecting a modernization configuration.

Table 2. Comparative characteristics of aeration systems under standard conditions (compiled by the author based on [11]).

Aerator type	SOTE (% per meter of depth)	SAE (kgO ₂ /kWh)	Notes
Surface aerator (low-speed)	—	1.5–2.1	High reliability, low efficiency
Jet aerator (Jet)	1.6–2.3	0.9–1.4	Effective for deep tanks
Fine-bubble diffusers (standard)	2.0–7.0	3.0–10.0	Leader in energy efficiency
High-density HDLF diffusers	3.0–8.0	5.0–13.0	Require high air cleanliness

A defining conclusion is the identified relationship between the density of bottom coverage in the aeration tank by aeration elements and the effectiveness of mass transfer. Increasing diffuser placement density reduces the airflow through a single element (flux), which raises SOTE by decreasing average bubble size and weakening bubble coalescence phenomena - factors that critically shape the interfacial contact area and, as a consequence, the

kinetics of oxygen transfer [11, 15]. In reconstruction practice for legacy facilities, the enterprise is systematically oriented toward increasing aerator coverage to 20–30% of the tank-bottom area, which creates the possibility of operating blower units in the minimum-load zone while achieving maximum efficiency. The description of aeration-system effectiveness is specified through the SOTR (Standard Oxygen Transfer Rate) indicator:

$$SOTR = K_l a \times C_{\infty,20} \times V_{(1)},$$

where:

$K_l a$ - volumetric mass-transfer coefficient (oxygen transfer coefficient);

$C_{\infty,20}$ - saturation concentration at 20 °C (9.09 mg/L);

V - liquid volume (water/mixed liquor) in the reactor or basin where O₂ transfer occurs.

Modernization implemented by plant engineering teams is directed toward maximizing SOTR by

optimizing diffuser layout and distribution across the tank bottom [11, 19]. Figure 3 presents the author's

schematic of an aeration-tank reconstruction with a

transition to an MBR configuration.

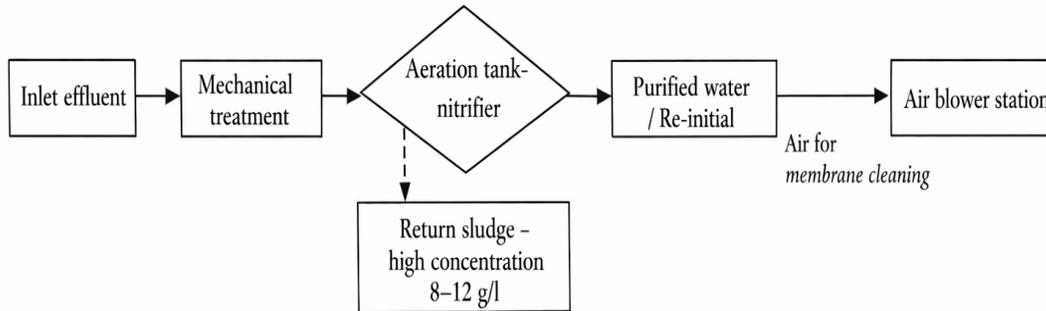


Fig.3. Author’s schematic of aeration-tank reconstruction with a transition to an MBR.

By 2023, the concept of “energy-neutral WWTPs” is becoming established as a de facto mandatory development benchmark for the sector [1, 18]. Within this paradigm, wastewater treatment plants can cover up to 40.8% of their own energy demand by tapping the

energy potential of biogas produced during sludge processing [21]. Table 3 provides a structured description of sludge energy potential in the reconstruction context.

Table 3. Energy potential of sludge during reconstruction (compiled by the author based on [3]).

Parameter	Unit	Value
Theoretical methane yield(B_{th})	$Nm^3 CH_4/kgV$	0,35
Biogas calorific value	MJ/m	21
Coverage of WWTP electricity demand	%	18
Savings	USD/year	223267

The methane-yield calculation is performed using the following formula:

$$B_{th} = 22,4 \times \frac{4a + b - 2c - 3d - 2e}{8(12a + b + 16c + 14d + 32e)} \quad (2),$$

The presented formula enables engineering teams to forecast the payback of digesters already at the feasibility-study stage of reconstruction, rather than discovering the economics “after the fact,” when capital decisions have effectively become irreversible [13, 16]. In 2023, the deployment of AI-based systems

makes it possible to manage dissolved oxygen (DO) concentration dynamically, shifting control from reactive adjustment to anticipatory regulation [17, 18]. Predictive algorithms account for weather forecasts and diurnal variations in influent flow, which is schematically illustrated in Figure 4.

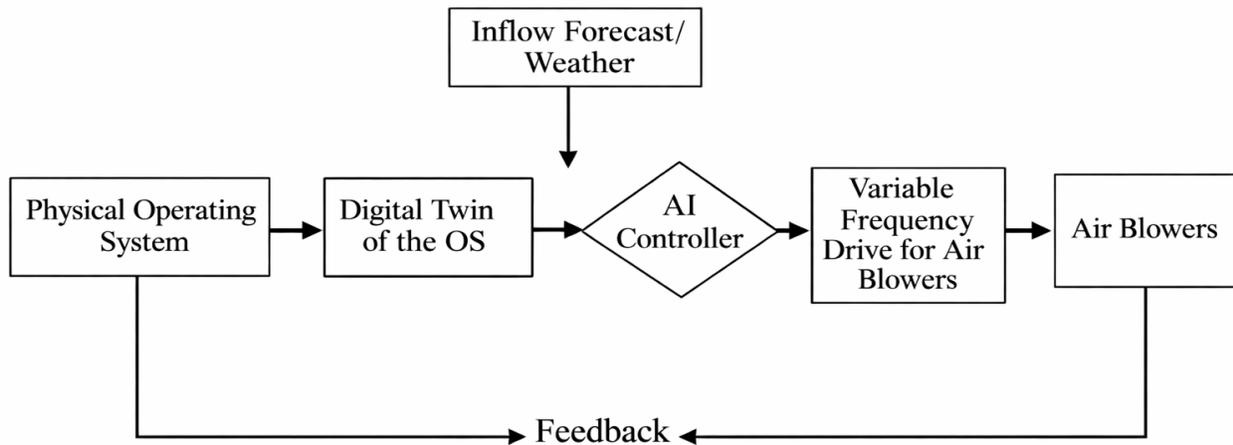


Fig.4. AI-based algorithm for managing energy consumption (compiled by the author based on [5,6,8]).

By 2023, implementation of a wastewater treatment plant “digital twin” is shifting from an optional practice to a standard engineering instrument, enabling continuous validation of operating modes and more immediate risk management [17]. Predictive maintenance - grounded in the analysis of vibration signals and temperature fluctuations of pumping equipment - materially reduces the probability of emergency shutdowns, the economic damage of which becomes critical under a continuous technological cycle [17].

A separate and increasingly practical value attaches to the use of artificial intelligence algorithms for adaptive correction of dissolved oxygen (DO) setpoints in aeration tanks as a function of current load and the state of the biological system. It has been shown that

reducing DO concentration by only 0.5 mg/L (from 2.0 to 1.5 mg/L) can lower blower energy consumption by up to 15% without deterioration of nitrogen-removal performance, underscoring how sensitive the plant energy balance is to aeration parameters when technological stability is preserved [1]. Integration of SCADA telemetry with weather forecasts further expands the scope of preventive management of hydraulic peaks: advance preparation for stormwater inflows makes it possible to optimize the operation of pumping stations and minimize the risk of activated-sludge washout by more precisely coordinating pumping, recirculation, and aerobic regimes.

Table 4 describes the effectiveness of digital optimization strategies.

Table 4. Effectiveness of digital optimization strategies (compiled by the author based on [1]).

Technology	Potential reduction in energy use	Expected effect
AI optimization of pumping stations	20–30%	Reduction of peak loads
Predictive maintenance (AI)	10–15%	Lower repair costs and downtime
Dynamic aeration control	15–25%	Optimization to actual load
Smart chemical dosing	5–10%	Savings in chemicals and feed energy

The analysis conducted reveals stable cause-and-effect relationships that may determine the sector's development trajectory over the medium term.

The tightening of environmental requirements for treated wastewater quality is objectively coupled with a rise in the energy intensity of the technological cycle. Achieving more elaborated regulatory acts for pollutant indicators requires the introduction of additional polishing stages, including tertiary and quaternary treatment, alongside an expanded set of equipment and instrumentation. Under 2023 conditions, a contradiction emerges between the task of reducing impacts on receiving waters and the task of lowering the carbon footprint of wastewater treatment plants; in practice, this contradiction is largely resolvable through technologically justified energy recovery, which can compensate for increased electricity consumption [7].

A material limiter of energy efficiency is the physical and functional obsolescence of infrastructure. Operation of legacy-generation pumping and blower

equipment is typically associated with a 15–25% decrease in efficiency compared with modern analogs, which translates into systematically inflated operating expenditures. Targeted replacement of two or three key units with models equipped with variable-frequency drives can deliver payback within 2–3 years as a result of electricity savings and the accounting of tariff dynamics [3].

In parallel, the functional role of wastewater treatment plants in the urban fabric is changing: from isolated sanitary-protection zones toward elements of resource infrastructure. Technologically grounded water reuse supported by contemporary membrane solutions (including membrane bioreactors) allows a substantial fraction of flow to be returned to technical circulation and reduces pressure on freshwater supply sources. This approach becomes particularly relevant for arid territories and large industrial hubs, where water scarcity begins to act as a factor of economic security.

From a legal perspective, the tendencies outlined

consolidate a shift from a predominantly “punitive” model of regulation toward a model of managed obligations, grounded in comparing environmental outcomes with total life-cycle costs. In that logic, requirements for discharges and technological parameters must inevitably be correlated with operating regimes, modernization availability, and objective limits of energy efficiency; otherwise, regulation provokes cost growth without a proportional environmental effect. A direct consequence is increased demand for legal mechanisms that stimulate modernization: integrated permitting regulation for environmentally significant facilities, application of technology-based standards, and the fixation of staged efficiency-improvement programs verified through industrial environmental monitoring.

Special attention is warranted for the resource potential of wastewater sludge as an object of legal and technological governance. Anaerobic digestion with biogas production and subsequent generation of thermal and electric energy, as well as phosphorus and nitrogen recovery from sludge-processing streams, forms an economically measurable “internal source” of energy and raw materials [13, 21]. As a result, energy recovery ceases to be an optional add-on and is increasingly treated as an element of proper technological organization - one that affects the attainment of environmental indicators while simultaneously reducing external energy demand.

The investment feasibility of the listed solutions is, to a substantial degree, determined by the quality of contractual-legal constructs and tariff regulation. For municipal infrastructure assets, concession agreements, energy service contracts, and models that allocate risks between the public party and the investor under a measurable resource-savings effect become

especially significant. With correct legal structuring, modernization ceases to depend exclusively on one-time capital expenditures and becomes a managed process in which electricity savings and resource recovery operate as sources of cost compensation, while control of performance indicators acquires legally meaningful status.

Conclusion

The study conducted confirms that improving the energy efficiency of wastewater treatment plants during reconstruction constitutes a multifactor task that requires alignment of technological, economic, and digital solutions within a single management contour. The results obtained indicate the priority status of modernizing biological treatment processes: transition to fine-bubble aeration and implementation of membrane bioreactors (MBRs) support intensified pollutant removal and improve the stability of treated effluent quality. At the same time, the increase in specific energy consumption associated with MBR operation - including energy expenditures for membrane scouring aeration that may reach 60% - is compensated by an aggregate effect through avoidance of capital construction for additional volumes, reduction of facility footprint, and production of water suitable for repeated technological reuse.

A distinct set of findings establishes the importance of measures aimed at the facility’s energy self-sufficiency. The average potential for covering a WWTP’s internal electricity demand is 40.8% when biogas cogeneration is utilized, which supports treating energy recovery not as an optional add-on but as a functionally necessary element of reconstruction. In this connection, construction and commissioning of anaerobic digesters is reasonably qualified as a required stage of modernization for large municipal plants, because sludge processing is precisely the subsystem that

forms the legal and economic basis for reducing dependence on external energy resources.

Digital transformation is considered as an independent factor for reducing operating costs and strengthening the robustness of treatment regimes. In 2023, the application of machine-learning algorithms in combination with variable-frequency drives makes it possible to achieve savings on the order of 25–30% in pumping stations and aeration systems by optimizing air supply and pumping rates, eliminating excessive operating modes, and responding promptly to fluctuations in hydraulic and pollutant loading. Of particular significance is the correct arrangement of measurements and the verification of digital models, because without reliable baseline data automation can devolve into a merely formal complication of control structures without a guaranteed energy effect.

The practical significance of the results is expressed in the need to normalize and ensure comparability of operational data arrays, enabling a technically defensible choice of modernization strategy. Comparative analysis of indicators (specific energy consumption, aeration efficiency, sludge-regime parameters, and losses in pumping systems) becomes critical under conditions of rising electricity prices, since errors in selecting technical solutions translate directly into long-term tariff and operational risks. As a result, reconstruction targets should be formulated not only through discharge-quality indicators but also through measurable energy metrics subject to subsequent verification and control.

Additionally, it appears justified to secure, i.e., to formally fix in design and operational documentation, a system of energy indicators reflecting the structure of electricity use across process stages. Wastewater treatment plants typically exhibit a concentration of energy demand in aeration and pumping blocks, which

objectively prioritizes measures aimed at improving oxygen transfer efficiency, reducing hydraulic losses, and optimizing blower operation. Establishing permissible ranges of specific energy consumption by treatment type and actual loading allows energy efficiency to be moved from a declarative category into a parameter amenable to evidentiary verification during acceptance of reconstructed facilities.

Separate attention should be devoted to the development of predictive maintenance instruments and life-cycle management of equipment. Deployment of automated dispatching systems and continuous monitoring of vibration, temperature, and electrical parameters of motor drives reduces accident rate, i.e., incident frequency, and prevents hidden energy losses that arise as pumps and blowers experience degradation of operating characteristics. When combined with digital process models, this supports an operationally manageable regime in which decisions on repair or replacement are taken on the basis of objective performance indicators rather than post-failure necessity.

From an economic and legal standpoint, the proposed model of energy-efficient reconstruction requires ensuring measurability of outcomes and their legally meaningful fixation in contractual and design documentation. The energy effect must be subject to confirmation through a regulated procedure of metering and control, because only in that case do mechanisms that link investments with subsequent resource savings become workable, including the allocation of risks across capital expenditures and operational performance indicators.

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