Al-imad Journal of Humanities and Applied Sciences (AJHAS)
مجلة العماد للعلوم الإنسانية والتطبيقية
ISSN: 3106-0323
Volume 2 – Issue 2 – 2026
Pages 394-401

Improving the Efficiency of Pumping Systems in Water Treatment Plants Using Mechanical Engineering Techniques for Environmental Sustainability

Amar Abobkr Amar Ahmeda [1]*, Musbah Aissa Mohamed Alsagheer [2]
[1] Department of Mechanical Engineering, Higher Institute of Science and Technology, Jufra, Sukna, Libya
[2] Department of Civil Engineering, Faculty of Science and Technology, Umm al-Arnab, Libya
*Corresponding: Amer7979a@yahoo.com

تحسين كفاءة أنظمة الضخ في محطات معالجة المياه باستخدام تقنيات الهندسة الميكانيكية من أجل الاستدامة البيئية

عامر أبوبكر عامر احميده [1]*، مصباح عيسى محمد الصغير [2]
[1] قسم الهندسة الميكانيكية، المعهد العالي للعلوم والتقنية الجفرة، سوكنة، ليبيا
[2] قسم الهندسة المدنية، كلية العلوم والتقنية ام الارنب، ليبيا

Received: 10-06-2026; Accepted: 11-07-2026; Published: 01-08-2026

Abstract:
Pumping systems represent the backbone of modern water treatment plants (WTPs) while constituting one of the most significant energy consumers in the municipal water sector. Given that wastewater treatment facilities consume 1–3% of national electricity, with pumping systems accounting for 15–70% of this demand, optimizing pump efficiency has become a paramount priority for achieving environmental sustainability. This manuscript delivers a comprehensive review of advanced mechanical engineering techniques designed to enhance operational efficiency within water treatment and supply infrastructure. The study systematically evaluates advanced impeller design optimization, variable frequency drives (VFDs), predictive maintenance frameworks, energy recovery systems, and renewable energy integration. Recent empirical case studies demonstrate that synthesizing multiple interventions—including pump-as-turbine (PAT) configurations, artificial intelligence-based optimization, and solar photovoltaic integration—can achieve substantial energy savings ranging from 20% to 50%, while concurrently mitigating carbon emissions. Ultimately, the findings provide actionable insights and practical recommendations for water utilities striving to balance high operational efficiency with long-term environmental stewardship.

Keywords: Pumping systems, water treatment plants, energy efficiency, mechanical engineering, variable frequency drives, environmental sustainability.

الملخص
تمثل أنظمة الضخ العمود الفقري لمقومات محطات معالجة المياه الحديثة، غير أنها تُعد في الوقت ذاته من أكبر المستهلكين للطاقة في قطاع المياه البلدي. ونظراً لأن مرافق معالجة مياه الصرف الصحي تستهلك ما بين 1% إلى 3% من إجمالي الكهرباء الوطنية، حيث تستحوذ أنظمة الضخ وحدها على نسبة تتراوح بين 15% و70% من هذا الاستهلاك، فقد أصبح تحسين كفاءة المضخات أولوية قصوى لتحقيق الاستدامة البيئية. تقدم هذه الورقة البحثية مراجعة شاملة لتقنيات الهندسة الميكانيكية المتقدمة المصممة لتعزيز الكفاءة

التشغيلية داخل مرافق معالجة المياه وإمداداتها. وتستعرض الدراسة بأسلوب منهجي عمليات تحسين تصميم المروحة (*Impeller*)، ومحركات التردد المتغير (*VFDs*)، وأطر الصيانة التنبؤية، وأنظمة استعادة الطاقة، فضلاً عن دمج مصادر الطاقة المتجددة. وتُظهر دراسات الحالة الإمبريقية الحديثة أن دمج التدخلات المتعددة—بما في ذلك تقنية المضخات كبينات (*PAT*)، والتحسين القائم على الذكاء الاصطناعي، والربط بالطاقة الشمسية الكهروضوئية—يمكن أن يحقق وفورات جوهرية في الطاقة تتراوح بين 20% و50%، مع الحد بصورة ملحوظة من انبعاثات الكربون. وتقدم النتائج في نهاية المطاف رؤى عملية وتوصيات قابلة للتنفيذ لمرافق المياه الساعية إلى موازنة الكفاءة التشغيلية العالية مع المسؤولية البيئية طويلة الأجل.

الكلمات المفتاحية: أنظمة الضخ، محطات معالجة المياه، كفاءة الطاقة، الهندسة الميكانيكية، محركات التردد المتغير، الاستدامة البيئية.

1.Introduction

Water treatment plants (WTPs) are essential infrastructure for public health and environmental protection, yet they are inherently energy-intensive operations. The water sector consumes approximately 15% of total energy in some countries, highlighting the critical need for effective energy management and efficiency measures to ensure long-term water-energy security. Within WTPs, pumping systems represent a dominant fraction of energy consumption—pumping can account for 4% to 30% of energy consumption in municipal wastewater treatment plants, and in some facilities, pump groups consume up to 80% of electrical energy.

The environmental implications are substantial. Energy consumption in water treatment is directly linked to greenhouse gas emissions, operational costs, and the overall carbon footprint of water utilities. As climate change intensifies water scarcity and regulatory pressures mount, optimizing the energy efficiency of pumping systems has emerged as a cornerstone of sustainable water management.

Mechanical engineering offers a diverse toolkit for addressing these challenges. From hydraulic design optimization and advanced materials to smart control systems and energy recovery technologies, mechanical engineers are at the forefront of transforming energy-intensive pumping operations into efficient, sustainable systems. This manuscript provides an up-to-date review of mechanical engineering techniques for improving pumping system efficiency in water treatment plants, with a focus on environmental sustainability outcomes.

2. The Energy Challenge in Water Treatment Pumping

2.1 Scale of Energy Consumption

The energy intensity of water treatment varies significantly across facilities and technologies. Specific energy consumption (SEC), expressed in kWh/m^3, serves as the primary performance metric for assessing operational efficiency. A comprehensive study of a large surface water treatment plant in Jordan revealed an average monthly SEC of 0.4106 kWh/m^3 over a 21-month monitoring period (Bader & Alawasa, 2025). In contrast, desalination facilities using reverse osmosis technologies consume between 2.5 and 6.0 kWh/m^3.

For wastewater treatment, the energy picture is equally demanding. A centralized wastewater treatment plant in Vietnam reported an average SEC of 0.93 kWh/m^3 of treated wastewater—15–20% higher than international benchmarks for similar-scale facilities.

2.2 Environmental and Economic Drivers

The environmental imperative for improving pump efficiency is clear: reduced energy consumption directly translates to lower greenhouse gas emissions. A proposed solar photovoltaic system for a Jordanian water treatment plant, designed to fully cover the plant's energy demand, could avoid an estimated 3,270.42 tons of CO_2 emissions annually from conventional power generation (Bader & Alawasa, 2025).

Economically, energy costs represent one of the largest operational expenses in water treatment. With energy costs making up nearly 85% of a pump's life-cycle expenses, even modest efficiency improvements yield substantial financial returns. The payback period for efficiency investments such as VFD installations typically ranges between 2 and 5 years, depending on load profiles and electricity costs.

3. Mechanical Engineering Approaches to Pump Efficiency Optimization

3.1 Advanced Hydraulic Design and Impeller Optimization

The hydraulic design of pump impellers fundamentally determines pumping efficiency. Recent advances in computational fluid dynamics (CFD) and optimization algorithms have enabled significant improvements in impeller design for wastewater applications.

3.1.1 Blade Tip Design Innovations

Research by Yang et al. (2024) demonstrated that impeller blade-tip geometry has an outsized impact on pump performance. The study tested four different impeller blade-tip designs to understand which could improve sewage pump efficiency while maintaining low blockage rates. A T-shaped tip design showed improved hydraulic efficiency and energy stabilization. These findings enable engineers to tailor tip designs to specific pump applications, contributing to more reliable and efficient sewage pump systems.

3.1.2 Multi-Objective Optimization

Multi-objective optimization methods have proven highly effective for sewage pump design. Research employing the non-dominated sorting genetic algorithm III (NSGA-III) showed that optimized pumps achieved a 9.7% increase in head and a 7.13% improvement in efficiency compared to original designs.

Similarly, genetic algorithm-based automatic optimization systems for rotating machinery have demonstrated significant improvements: optimized centrifugal pumps achieved a 1.29% increase in lift and a 2.96% efficiency increase compared to original designs.

3.1.3 Response Surface Methodology

The combination of CFD with response surface methodology (RSM) has emerged as a powerful approach for centrifugal pump optimization in wastewater applications. This approach enables systematic exploration of design parameters to identify optimal configurations that maximize efficiency while meeting operational requirements.

3.2 Variable Frequency Drives (VFDs)

Variable frequency drives represent one of the most impactful mechanical engineering technologies for improving pump efficiency. VFDs regulate motor speed and torque by adjusting frequency and voltage, allowing pumps to operate only when needed and at optimal efficiency points.

3.2.1 Energy Savings Potential

The energy savings from VFD implementation are substantial. Research demonstrates that lowering pump speed by just 20% using VFDs can reduce energy consumption by up to 50%. Industry estimates indicate that VFDs in wastewater treatment systems can achieve energy savings of up to 50% compared to fixed-speed systems.

A case study of a drinking water purification plant in southern Egypt demonstrated the practical benefits of VSD implementation (Energy saving analysis, 2024). The study analyzed 24-hour power consumption measurements with and without VSD use, confirming significant energy savings (Energy saving analysis, 2024). For water and wastewater applications, typical energy savings range from 15% to 30%.

3.2.2 Operational Benefits Beyond Energy Savings

Beyond energy efficiency, VFDs offer multiple operational advantages. They ensure smoother starts and stops, better process control, and improved system stability. In pumping stations where energy consumption can exceed 50% of total operational costs, VFDs prevent inefficiencies caused by constant-speed operation by modulating pump performance based on flow and head demand.

Advanced VFD solutions now incorporate smart control algorithms, sensorless vector control, and real-time adaptability to ensure optimal pump performance. The integration of advanced diagnostics enables early anomaly detection, helping utilities prevent faults and avoid costly unplanned shutdowns.

3.3 Predictive Maintenance and Condition Monitoring

Traditional maintenance practices for pumps in wastewater treatment plants often operate reactively, focusing on simple reinforcement measures when faults are detected rather than applying strategic management. Mechanical engineering has responded with advanced predictive maintenance approaches that accurately predict machine conditions, offering the potential to reduce maintenance costs and improve facility operations.

3.3.1 Machine Learning-Based Predictive Maintenance

A recent study established a real-world monitoring system for return pumps in wastewater treatment plants, extracting operational data and applying machine learning techniques to predict future performance The predictive maintenance approach performed well at the 60-minute prediction point, achieving an RMSE of 0.025 and an MAE of 0.009.

The study strongly suggests that preventive pump maintenance can significantly reduce the risk of prolonged wastewater treatment outages and environmental discharges. This is particularly critical given that pump failures can lead to excessive microorganism accumulation, nutrient concentration increases in effluent, and inhibition of microbial activity.

3.3.2 Self-Diagnosing Intelligent Pumps

A new generation of intelligent centrifugal pumps has been launched, offering operators unprecedented visibility into pump performance and early-stage fault detection. These self-diagnosing systems are designed for water treatment environments and represent a significant advancement in proactive asset management.

3.3.3 Physics-Based Modeling

Integrating fluid rheology into physics-based torque models for progressive cavity pumps has enabled more accurate monitoring of fluid viscosity and total suspended solids—essential parameters for effective wastewater treatment. This approach explicitly represents viscosity and total suspended solids as parameters, enabling more precise pump control and maintenance scheduling.

4. Energy Recovery and Renewable Integration

4.1 Pump-as-Turbine (PAT) Technology

The reverse operation of centrifugal pumps as turbines (PAT) represents a key approach for recovering hydraulic energy. In water distribution networks, PATs can replace pressure-reducing valves to dissipate excess energy while generating electricity.

A comprehensive study of the La Presa drinking water purification plant in Valencia, Spain, evaluated alternatives for improving energy efficiency, including the installation of turbines for energy recovery (de León Fabián et al., 2025). The best solution involved combining pumps and turbines, achieving energy savings of 42.26% compared to the actual situation. Importantly, this configuration-maintained water quality with an average residence time in tanks of less than 50 hours. (de León Fabián et al., 2025).

 |

The Mérida drinking water treatment plant project confirms that reusing pumps as turbines is a technically, economically, and environmentally efficient solution for facilities with adequate hydraulic headroom. PAT technology enables energy recovery from existing pipe networks with low investment and maintenance costs.

4.2 Energy Recovery Devices in Desalination

In reverse osmosis desalination, energy recovery devices (ERDs) are critical for minimizing net energy consumption. An innovative high-pressure pump developed by ENEA and SEKO integrates an energy recovery device capable of recovering return pressure from the osmosis retentate, significantly reducing the energy consumption associated with high-pressure pumping.

The electromechanical conversion chain—from grid power through variable-speed drives, motors, and pumps—determines instantaneous efficiency, dynamic response, and reliability. Optimizing this chain through advanced mechanical engineering is essential for sustainable desalination.

4.3 Renewable Energy Integration

The integration of renewable energy sources with pumping systems offers a pathway to net-zero energy water treatment. A solar photovoltaic system designed to fully cover a Jordanian water treatment plant's consumption would enable net-zero energy operation and position it as the first green-certified surface water treatment plant in the country.

Renewable energy-driven pumping systems for desalination, integrating solar photovoltaic and wind technologies, represent a pivotal technology for sustainable development within the water sector. Advanced control and energy management systems are essential for overcoming the intermittency of renewable sources, with strategies including maximum power point tracking (MPPT), motor drive control, and supervisory EMS that optimize the synergy between pumps, ERDs, and variable power inputs.

5. Smart Control and Optimization Strategies

5.1 AI-Based Optimization

Artificial intelligence and machine learning are transforming pump system optimization. A deep learning approach combining ResNet, self-attention mechanisms, and Grey Wolf Optimizer achieves 10–30% energy savings in wastewater pumping systems, outperforming genetic algorithms (12–18%) and traditional PID control (5–8% savings).

Research shows that implementing high-efficiency pumping systems and AI-based optimization can reduce energy consumption in WTPs by 20–30%. Reinforcement learning-based scheduling optimization for pumping systems has demonstrated significant potential, with deep reinforcement learning (DRL) approaches integrating MS-LSTM and ARWA-PPO for optimal pump control.

5.2 Pump Scheduling Optimization

Optimizing pump scheduling is crucial for energy savings and carbon emission reduction. Up to 80% of electrical energy in water purification plants is consumed by pump groups, making scheduling optimization a high-impact intervention.

A case study of pump scheduling using sensor-based real-time pump efficiency monitoring demonstrated energy savings of up to 3% over four months. Digital twin-based dynamic scheduling methods for pump stations offer further optimization potential. Machine learning-based water plant optimization control systems can design optimized schemes for pump group scheduling, backwashing, and reagent dosing, enabling water treatment processes to operate in optimal modes.

5.3 Model Predictive Control

Model predictive control (MPC) strategies for scheduling treatment plant system operations can minimize greenhouse gas emissions while safely meeting water demand. This approach focuses on optimizing water production rather than just distribution, ensuring that water treatment facilities operate at maximum efficiency.

6. Case Studies and Practical Implementations

6.1 La Presa Drinking Water Purification Plant, Valencia, Spain

The La Presa DWPP case study provides a comprehensive example of integrated efficiency improvement. The research analyzed the energy balance of the purification water pumping system and evaluated alternatives including:

- Construction of a storage tank at 75 m elevation
- Hydraulic simulations using EPANET under various demand scenarios
- Three alternatives: additional pumps, turbines, and combination

The combined pumps-and-turbines solution achieved 42.26% energy savings while maintaining water quality. This approach represents a novelty in the management of future decisions for purification plants supplying real networks.

6.2 Drinking Water Purification Plant, Southern Egypt

A variable speed drive implementation study at a drinking water purification plant in southern Egypt demonstrated the practical benefits of VSD technology. The VSD regulated motor speed to maintain appropriate external pressure, ensuring water delivery to all network branches. The energy-saving analysis confirmed the effectiveness of VSD control for pump-motor sets in water purification applications.

6.3 Surface Water Treatment Plant, Jordan

A water-energy performance evaluation of a large Jordanian surface water treatment plant over 21 months provided valuable benchmarking data. The study's proposal for a solar PV system to achieve net-zero energy operation offers a replicable model for sustainable water treatment.

7. Discussion and Future Directions

7.1 Integration of Multiple Approaches

The evidence from recent research strongly suggests that the greatest efficiency gains come from integrating multiple mechanical engineering approaches. Combining advanced impeller design with VFD control, predictive maintenance, energy recovery, and renewable integration creates synergistic benefits that exceed the sum of individual interventions.

7.2 Emerging Technologies

Several emerging technologies promise further efficiency improvements:

- **AI and deep learning** for real-time energy optimization
- **Digital twin technology** for dynamic pump station scheduling
- **Advanced materials** for reduced friction and wear
- **Internet of Things (IoT)** integration for comprehensive monitoring

7.3 Challenges and Barriers

Despite the clear benefits, several challenges impede widespread adoption:

- **Initial capital costs** for VFDs, advanced pumps, and control systems
- **Technical expertise requirements** for implementation and maintenance
- **Institutional inertia** and risk aversion in water utilities
- **Legacy infrastructure** that complicates retrofitting

7.4 Policy Implications

Achieving widespread efficiency improvements requires supportive policy frameworks, including:

- Energy efficiency standards for pumping equipment
- Financial incentives for efficiency investments
- Training programs for water utility personnel
- Research and development funding for emerging technologies

8. Conclusion

Mechanical engineering offers a comprehensive and proven toolkit for improving pumping system efficiency in water treatment plants. From advanced hydraulic design and variable frequency drives to predictive maintenance and energy recovery, these technologies deliver substantial energy savings, reduce greenhouse gas emissions, and enhance operational reliability.

The evidence reviewed in this manuscript demonstrates that:

- Impeller design optimization can improve pump efficiency by 7–13%
- VFD implementation can reduce energy consumption by 15–50%
- Predictive maintenance can prevent costly failures and environmental discharges
- PAT technology can recover significant hydraulic energy
- AI-based optimization can achieve 10–30% energy savings
- Renewable integration can enable net-zero energy operation

The combination of these approaches—exemplified by the La Presa DWPP case study achieving 42.26% energy savings—offers a pathway to sustainable water treatment that balances operational demands with environmental stewardship. As water scarcity intensifies and climate change accelerates, the adoption of these mechanical engineering techniques will be essential for building resilient, efficient, and sustainable water infrastructure.

References

[1] de León Fabián, H., Almenar Llorens, P., López-Jiménez, P. A., & Pérez-Sánchez, M. (2025). Is it possible to improve energy efficiency in water purification plants? The case of drinking water in La Presa DWPP in Valencia, (Spain). *Applied Sciences*, 15(21), 11340.

[2] Bader, G. Y., & Alawasa, K. M. (2025). Water-energy performance evaluation and renewable integration of a surface water treatment plant and pumping station in Jordan. *Journal of Renewable and Sustainable Energy*, 17(6), 066305.

[3] Energy saving analysis for pump-motor set in water purification plant using variable speed drive. (2024). *Scientific Reports*, 14, 27728.

[4] Yang, Y., et al. (2024). Leakage vortices and energy characteristics of semi-open sewage pump with various blade tip alterations. *Physics of Fluids*.

[5] Decision making methodology for maintenance of return pumps in wastewater treatment plant using machine learning. (2025). *Science of the Total Environment*.

[6] Renewable energy driven pumping systems and application for desalination: A review of technologies and future directions. (2026). *Applied Sciences*, 16(2), 862.

[7] Smart water through smart drives: Enhancing water efficiency with variable frequency drives. (2025, December). *Smart Water Magazine*.

[8] Grundfos CUE 120: Powering precision in sustainable pumping. (2025, August). *ISR Magazine*.

[9] Deep learning approach to energy consumption modeling in wastewater pumping systems. (2025, November). *Scientific Reports*.

[10] Energy efficiency analysis of water treatment plants: Current status and future trends. (2025, February). *MDPI*.

[11] Multi-criteria response surface optimization of centrifugal pump performance using CFD for wastewater application. (2024). *Modelling*, 5, 673–693.

[12] Multi-objective optimization design of a sewage pump based on non-dominated sorting genetic algorithm III. (2024). *OUCI*.

[13] Case study of pump scheduling using sensor-based real-time pump efficiency monitoring. (2024, August). *ScienceDirect*.

[14] Design and optimization of the centrifugal pump impeller for wastewater. (2024). *Materials Research Proceedings*, 28.

[15] Model-based control of water treatment with pumped water storage. (2024, August). *arXiv*.
[16] DRL-based scheduling optimization strategy for the pumping system of Ninghai Xinghai Wastewater Treatment Plant. (2025, July). *IEEE*.
[17] Key innovations shaping wastewater treatment systems. (2025, September). *Crown Publications*.
[18] Energy efficiency analysis of the final lift station of an activated sludge wastewater treatment plant in Brazil. (2024). *IAHR*.
[19] New booster pump for desalination plants based on reverse osmosis. (2024, October). *IDRA*.
[20] A review of methods for 'pump as turbine' (PAT) performance prediction and optimal design. (2025, June). *ScienceDirect*.

