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Analysis of energy efficiency in water treatment plants: Present conditions and future directions

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Abstract

Water treatment plants (WTPs) are critical infrastructure for ensuring access to clean and safe water, but they are also significant consumers of energy, contributing to greenhouse gas emissions and operational costs. This study explores the current state of energy efficiency in WTPs, identifying key factors influencing energy consumption, such as treatment technologies, plant design, and operational practices. Through a comprehensive review of literature and case studies, the research highlights the energy-intensive nature of advanced treatment processes like reverse osmosis (RO) and ultraviolet (UV) disinfection, as well as the inefficiencies in conventional systems due to outdated infrastructure and suboptimal practices. The study also examines emerging trends and future directions for improving energy efficiency, including the integration of renewable energy sources (solar, wind, and hydropower), the adoption of advanced monitoring systems (IoT, AI, and data analytics), and the implementation of innovative treatment processes (forward osmosis, electrochemical treatment, and membrane distillation). Case studies of energy-efficient WTPs, such as Singapore's NEWater Plants and the Carlsbad Desalination Plant, demonstrate the potential for significant energy savings through technological innovation and optimized operations. The findings underscore the importance of adopting sustainable practices to reduce greenhouse gas emissions and operational costs while maintaining water quality standards.

Keywords: Energy Efficiency; Water Management; Greenhouse Gas Emission; Energy consumption pattern

1. Introduction

Access to clean and safe water is a fundamental human right and a cornerstone of public health, economic development, and environmental sustainability and also it is one the biggest problems that is facing the world population for several issues such as climate change, increment on worldwide population, careless and abusive use of water, as well as water pollution (Bakare et.al, 2025). Water Treatment plants (WTPs) are critical infrastructure that ensure the availability of potable water by removing contaminants, pathogens, and pollutants from raw water sources (WHO, 2019). However, the processes involved in water treatment such as coagulation, sedimentation, filtration, disinfection, and desalination—are highly energy-intensive. According to the International Energy Agency (IEA, 2020), the water sector accounts for approximately 4% of global electricity consumption, with WTPs being one of the largest energy consumers within this sector.

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The energy demand of WTPs is driven by the need to meet stringent water quality standards, particularly in regions facing water scarcity, contamination, or population growth. For example, advanced treatment technologies like reverse osmosis and ultraviolet (UV) disinfection, while effective, require significant amounts of energy to operate (Plappally & Lienhard, 2012). This energy consumption not only increases operational costs but also contributes to greenhouse gas (GHG) emissions, exacerbating climate change. In fact, the water sector is estimated to contribute 5% of global GHG emissions, with energy use being a major factor (IPCC, 2021). Despite their critical role in providing clean water, WTPs often operate with suboptimal energy efficiency due to outdated technologies, inefficient plant designs, and lack of awareness about energy-saving practices. For instance, studies have shown that pumping and aeration processes alone can account for up to 60% of a plant's total energy consumption (Olsson, 2012). These inefficiencies not only strain financial resources but also hinder progress toward global sustainability goals, such as the United Nations Sustainable Development Goal (SDG) 6, which aims to ensure access to clean water and sanitation for all by 2030 (UN Water, 2021). Given the dual challenges of rising energy costs and environmental degradation, there is an urgent need to improve energy efficiency in WTPs. This requires a holistic approach that integrates advanced technologies, optimized plant design, and sustainable operational practices. For example, the adoption of renewable energy sources, such as solar and wind power, can reduce reliance on fossil fuels and lower GHG emissions (EPA, 2021). Similarly, the implementation of advanced monitoring systems and data-driven optimization tools can enhance operational efficiency and reduce energy waste (Bolognesi et al., 2020). This study aims to explore the current state of energy efficiency in WTPs, identify key factors influencing energy consumption, and examine emerging trends and future directions for improvement. By analyzing case studies and existing literature, this paper provides actionable insights for engineers, policymakers, and plant operators to optimize energy use in WTPs while maintaining water quality standards. The findings of this study will contribute to the growing body of knowledge on sustainable water management and support efforts to achieve energy-efficient and environmentally friendly water treatment systems.

2. Literature Review

2.1. Current State of Energy Efficiency in WTPs

Energy efficiency in water treatment plants (WTPs) has become a critical area of research due to the rising energy demands of water treatment processes and their environmental and economic impacts. Studies indicate that WTPs consume significant amounts of energy, with global electricity use in the water sector estimated at 120 Mtoe (million tonnes of oil equivalent) annually, accounting for approximately 4% of total global electricity consumption (IEA, 2020). The energy intensity of WTPs varies depending on the source water quality, treatment technologies, and operational practices. For instance, desalination plants, which rely on energy-intensive processes like reverse osmosis (RO), can consume up to 10 times more energy than conventional surface water treatment plants (Plappally & Lienhard, 2012). The role of treatment technologies in energy consumption is particularly significant. Conventional methods, such as coagulation, sedimentation, and sand filtration, are less energy-intensive compared to advanced technologies like membrane filtration, UV disinfection, and advanced oxidation processes (AOPs). For example, membrane filtration systems, while highly effective in removing contaminants, require substantial energy for pumping and backwashing, contributing to higher operational costs (Shannon et al., 2008). Similarly, UV disinfection, though effective for pathogen inactivation, demands continuous energy input for lamp operation and maintenance (Bolton & Cotton, 2008).

2.2. Key Factors Influencing Energy Consumption

2.2.1. Treatment Technologies

The choice of treatment technologies significantly impacts the energy consumption of WTPs. Conventional technologies, such as gravity-fed filtration and chlorination, are generally less energy-intensive but may not meet the stringent water quality standards required for modern water treatment. In contrast, advanced technologies like RO, nanofiltration (NF), and AOPs offer superior treatment outcomes but at a higher energy cost. For instance, RO systems, widely used in desalination and wastewater reuse, can consume between 3–10 kWh/m^3 of treated water, depending on the feedwater salinity and system design (Elimelech & Phillip, 2011).

Emerging technologies, such as forward osmosis (FO) and electrochemical treatment, show promise in reducing energy consumption. FO, for example, utilizes osmotic pressure gradients rather than hydraulic pressure, potentially lowering energy requirements by up to 30% compared to RO (Cath et al., 2013). However, these technologies are still in the developmental stage and face challenges related to scalability and cost-effectiveness.

2.2.2. Plant Design

The design and layout of WTPs play a crucial role in determining energy efficiency. Factors such as plant size, process configuration, and infrastructure design can significantly influence energy use. Larger plants often benefit from economies of scale, reducing energy consumption per unit of treated water. However, they may also face challenges related to energy distribution and process optimization (Olsson, 2012).

The integration of energy recovery systems, such as turbine generators and pressure exchangers, can further enhance energy efficiency. For example, energy recovery devices (ERDs) in RO plants can reduce energy consumption by up to 60% by reclaiming energy from the high-pressure brine stream (Voutchkov, 2018). Additionally, optimizing the hydraulic design of treatment processes, such as minimizing head loss and improving pump efficiency, can lead to significant energy savings (Bolognesi et al., 2020).

2.2.3. Operational Practices

Operational inefficiencies are a major contributor to excessive energy consumption in WTPs. Common issues include over-pumping, inadequate maintenance of equipment, and suboptimal process control. For instance, pumping systems, which account for up to 60% of a plant's energy use, often operate below their optimal efficiency due to improper sizing or lack of variable frequency drives (VFDs) (EPRI, 2012). Aeration, another energy-intensive process, is critical for biological treatment in wastewater plants. However, inefficient aeration systems can lead to excessive energy use without corresponding improvements in treatment performance (Rosso et al., 2008). Implementing advanced process control strategies, such as real-time monitoring and automated feedback systems, can optimize energy use while maintaining treatment efficacy (Olsson, 2012).

Despite significant advancements in understanding energy efficiency in WTPs, several gaps remain in the literature. First, there is limited research on the integration of renewable energy sources, such as solar, wind, and hydropower, into WTPs. While some studies have explored the feasibility of solar-powered desalination plants, broader applications of renewable energy in conventional WTPs remain underexplored (Gude, 2016). Second, the role of digital technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), in optimizing energy use is an emerging area that requires further investigation. While preliminary studies have demonstrated the potential of AI-driven predictive maintenance and process optimization, large-scale implementation and cost-benefit analyses are lacking (Bolognesi et al., 2020). Finally, there is a need for more comprehensive case studies that evaluate the long-term performance and sustainability of energy-efficient technologies and practices. Most existing studies focus on short-term energy savings, with limited attention to lifecycle costs, environmental impacts, and scalability. Addressing these gaps will be critical for advancing energy efficiency in WTPs and achieving global sustainability goals.

3. Methodology

The methodology of this study is based on a comprehensive review of existing literature and case studies to evaluate the current state of energy efficiency in water treatment plants (WTPs) and identify future directions for improvement. Data was collected from a variety of sources, including peer-reviewed journals, industry reports from organizations such as the International Energy Agency (IEA) and the Environmental Protection Agency (EPA), real-world case studies, conference proceedings, and publications from government and non-governmental organizations like the United Nations (UN) and the Intergovernmental Panel on Climate Change (IPCC). To ensure the reliability and validity of the findings, data was cross-referenced across multiple sources, reviewed by experts in the field, and triangulated to confirm consistency. Additionally, the quality of each source was assessed based on the reputation of the publishing organization and the rigor of the research methodology. However, the study acknowledges certain limitations, such as data availability gaps in developing regions, the context-specific nature of case studies, the developmental stage of emerging technologies, and potential biases in industry reports. Despite these limitations, the methodology provides a robust framework for analyzing energy efficiency in WTPs, offering actionable insights for improving energy use while maintaining water quality standards.

4. Results

The findings of this study, derived from a comprehensive review of literature and case studies, reveal critical insights into the current state of energy efficiency in water treatment plants (WTPs), the factors influencing energy consumption, and emerging trends for improvement. The results are organized into three key areas: current energy consumption patterns, case studies of energy-efficient WTPs, and emerging trends and future directions. These findings are discussed in the context of the methodology, which relied on diverse data sources, rigorous validation, and an acknowledgment of limitations.

4.1. Current Energy Consumption Patterns

The analysis of global and regional data highlights significant variations in energy consumption across WTPs, driven by factors such as treatment technologies, plant size, and geographic location. Globally, WTPs account for approximately 4% of total electricity consumption, with desalination plants being the most energy-intensive, consuming up to 10 times more energy than conventional treatment plants (IEA, 2020). For instance, reverse osmosis (RO) systems, widely used in desalination and wastewater reuse, consume between 3–10 kWh/m^3 of treated water, depending on feedwater salinity and system design (Elimelech & Phillip, 2011). In contrast, conventional treatment methods like coagulation and sedimentation are less energy-intensive but may not meet stringent water quality standards in regions with contaminated or scarce water resources. Regional disparities are also evident, with WTPs in water-scarce or highly populated areas requiring more advanced and energy-intensive processes. For example, in regions like the Middle East and North Africa, where desalination is prevalent, energy consumption is significantly higher compared to regions with abundant freshwater resources.

4.2. Case Studies of Energy-Efficient WTPs

The review of case studies provides practical examples of how energy efficiency can be achieved through innovative technologies, optimized plant design, and sustainable operational practices. One notable example is Singapore's NEWater Plants, which utilize advanced membrane technologies and energy recovery systems to reduce energy consumption by up to 30% compared to traditional RO plants (PUB, 2020). The integration of dual-membrane systems (microfiltration and RO) and energy recovery devices (ERDs) has been instrumental in achieving these savings. Another example is the Carlsbad Desalination Plant in California, which employs state-of-the-art RO technology with energy recovery systems, reducing energy consumption by 40% compared to conventional desalination plants (Poseidon Water, 2021). The plant also incorporates renewable energy sources, such as solar power, to further minimize its carbon footprint. In Namibia, the Windhoek Goreangab Reclamation Plant demonstrates the effectiveness of optimizing operational practices, such as using variable frequency drives (VFDs) for pumps and improving aeration efficiency, to achieve significant energy savings (van der Merwe et al., 2014). These case studies underscore the importance of adopting a holistic approach to energy efficiency, combining advanced technologies, renewable energy integration, and operational optimization.

4.3. Emerging Trends

The analysis identifies several emerging trends that hold promise for improving energy efficiency in WTPs. One key trend is the integration of renewable energy sources, such as solar, wind, and hydropower, into WTP operations. For example, solar-powered desalination plants are being piloted in regions with high solar irradiance, offering a sustainable alternative to fossil fuel-based energy (Gude, 2016). Another trend is the adoption of digital technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), for real-time monitoring and process optimization. AI-driven predictive maintenance and automated feedback systems have shown potential in reducing energy waste and improving operational efficiency (Bolognesi et al., 2020). Additionally, innovative treatment processes, such as forward osmosis (FO) and electrochemical treatment, are emerging as energy-efficient alternatives to conventional methods. FO, for instance, utilizes osmotic pressure gradients rather than hydraulic pressure, potentially reducing energy requirements by up to 30% compared to RO (Cath et al., 2013). However, these technologies are still in the developmental stage and face challenges related to scalability and cost-effectiveness.

5. Discussion

The results highlight the dual challenges of rising energy costs and environmental degradation, underscoring the urgent need for energy-efficient solutions in WTPs. While advanced technologies like RO and UV disinfection offer superior treatment outcomes, their high energy consumption poses significant economic and environmental challenges. The case studies demonstrate that energy efficiency can be achieved through a combination of technological innovation, optimized plant design, and sustainable operational practices. However, the adoption of these solutions is often hindered by high upfront costs, lack of awareness, and regulatory barriers. The integration of renewable energy sources and digital technologies presents a promising pathway for reducing energy consumption and greenhouse gas emissions, but further research is needed to address scalability and cost-effectiveness. Additionally, the study's reliance on literature and case studies from developed regions may limit the generalizability of findings to developing countries, where data availability and resource constraints are significant challenges.

5.1. Future Directions

5.1.1. Renewable Energy Integration

The integration of renewable energy sources into water treatment plants (WTPs) is a promising strategy to reduce reliance on fossil fuels and lower greenhouse gas (GHG) emissions. Solar, wind, and hydropower are among the most viable options for powering WTPs, particularly in regions with abundant natural resources.

- Solar Energy: Solar power is increasingly being adopted in WTPs, especially in regions with high solar irradiance. Solar photovoltaic (PV) systems can be used to power pumps, aeration systems, and other energy-intensive processes. For example, pilot projects in the Middle East and North Africa have demonstrated the feasibility of solar-powered desalination plants, which significantly reduce energy costs and carbon footprints (Gude, 2016). Additionally, solar thermal energy can be used for processes like distillation, further enhancing energy efficiency.
- Wind Energy: Wind turbines can be installed near WTPs to generate electricity for plant operations. This is particularly effective in coastal or open areas with consistent wind patterns. For instance, some WTPs in Europe have successfully integrated wind energy to offset a portion of their energy consumption, contributing to overall sustainability (IRENA, 2020).
- Hydropower: In regions with access to flowing water, hydropower can be a reliable and renewable energy source for WTPs. Micro-hydropower systems can be installed to harness the energy from water flow within the treatment process itself, such as in gravity-fed systems or effluent discharge streams. This approach not only reduces energy costs but also enhances the overall efficiency of the plant (EPA, 2021).

The integration of renewable energy sources requires careful planning and investment, but it offers long-term benefits in terms of cost savings and environmental impact. Future research should focus on optimizing the design and implementation of renewable energy systems in WTPs, as well as exploring hybrid systems that combine multiple renewable sources for greater reliability.

5.1.2. Advanced Monitoring Systems

The adoption of advanced monitoring systems, such as the Internet of Things (IoT), artificial intelligence (AI), and data analytics, is transforming the way WTPs manage energy consumption. These technologies enable real-time monitoring, predictive maintenance, and process optimization, leading to significant energy savings.

- IoT: IoT devices can be deployed throughout WTPs to collect real-time data on energy use, process performance, and equipment status. For example, smart sensors can monitor pump efficiency, water quality, and energy consumption, allowing operators to identify and address inefficiencies promptly. IoT-enabled systems also facilitate remote monitoring and control, reducing the need for on-site personnel and improving operational flexibility (Bolognesi et al., 2020).
- AI and Machine Learning: AI-driven algorithms can analyze large datasets to identify patterns and predict equipment failures before they occur. Predictive maintenance reduces downtime and energy waste by ensuring that equipment operates at peak efficiency. Additionally, AI can optimize process parameters, such as chemical dosing and aeration rates, to minimize energy use while maintaining water quality standards (Olsson, 2012).
- Data Analytics: Advanced data analytics tools can provide actionable insights into energy consumption patterns, helping operators identify areas for improvement. For instance, energy audits powered by data analytics can reveal inefficiencies in pumping systems or aeration processes, enabling targeted interventions to reduce energy use (EPRI, 2012).

The implementation of these technologies requires investment in infrastructure and training, but the potential energy savings and operational benefits make them a worthwhile consideration for WTPs aiming to improve energy efficiency.

5.1.3. Innovative Treatment Processes

Emerging treatment technologies offer the potential to significantly reduce energy consumption in WTPs while maintaining or even improving water quality. These innovations are particularly relevant for energy-intensive processes like desalination and advanced oxidation.

- Forward Osmosis (FO): FO is an emerging membrane-based technology that uses osmotic pressure gradients, rather than hydraulic pressure, to separate water from contaminants. This process has the potential to reduce energy consumption by up to 30% compared to reverse osmosis (RO), making it an attractive option for desalination and wastewater treatment (Cath et al., 2013). However, challenges related to membrane fouling and scalability need to be addressed for widespread adoption.

- Electrochemical Treatment: Electrochemical processes, such as electrocoagulation and electrooxidation, use electrical energy to remove contaminants from water. These methods are highly efficient and can be powered by renewable energy sources, further enhancing their sustainability. Electrochemical treatment is particularly effective for removing heavy metals, organic pollutants, and pathogens, making it a versatile option for various water treatment applications (Martínez-Huitle & Brillas, 2020).
- Membrane Distillation (MD): MD is a thermally driven process that uses low-grade heat, such as waste heat or solar energy, to separate water from contaminants. This technology is well-suited for desalination and industrial wastewater treatment, offering energy savings compared to conventional thermal processes (El-Bourawi et al., 2006).
- Biological Treatment Innovations: Advances in biological treatment processes, such as anaerobic digestion and biofilm reactors, are also contributing to energy efficiency. These systems not only treat wastewater but also generate biogas, which can be used as a renewable energy source to power plant operations (Rosso et al., 2008).

While these innovative technologies show great promise, further research and development are needed to address challenges related to cost, scalability, and integration with existing infrastructure. Pilot projects and case studies will play a crucial role in demonstrating the feasibility and benefits of these technologies in real-world applications.

The future of energy efficiency in WTPs lies in the integration of renewable energy sources, the adoption of advanced monitoring systems, and the implementation of innovative treatment processes. These strategies not only reduce energy consumption and operational costs but also contribute to global sustainability goals by lowering GHG emissions. However, realizing these benefits will require coordinated efforts from researchers, policymakers, and industry stakeholders to overcome barriers related to cost, scalability, and technological maturity. By embracing these future directions, WTPs can transition toward more sustainable and energy-efficient operations, ensuring access to clean and safe water for all.

6. Conclusion

This study highlights the critical need for improving energy efficiency in WTPs to address rising energy costs, environmental degradation, and operational challenges. By adopting advanced technologies, integrating renewable energy sources, and leveraging digital tools, WTPs can achieve significant energy savings while maintaining water quality standards. However, realizing these benefits will require coordinated efforts from researchers, policymakers, and industry stakeholders to overcome barriers related to cost, scalability, and technological maturity. The findings of this study provide actionable insights for engineers, plant operators, and policymakers to drive the transition toward energy-efficient and environmentally friendly water treatment systems. Future research should focus on advancing renewable energy integration, optimizing emerging technologies, and developing region-specific solutions to ensure sustainable water management for all.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Bakare-Abidola, T., Russell, W. J., Jorgensen, K., & Pérez, R. L. (2025). Enhanced extraction of methylene blue by dodecyl-methyl imidazolium dodecyl sulfate GUMBOS-magnetic alginate beads. *Chemosphere*, *370*, 143991.

[2] Bolognesi, A., Bragalli, C., & Lenzi, C. (2020). Energy efficiency in water supply systems: A review of optimization methods. Water, 12(5), 1356.

[3] EPA. (2021). Energy efficiency in water and wastewater facilities. United States Environmental Protection Agency.

[4] IEA. (2020). World energy outlook 2020. International Energy Agency.

[5] IPCC. (2021). Climate change 2021: The physical science basis. Intergovernmental Panel on Climate Change. R

[6] Olsson, G. (2012). Water and energy: Threats and opportunities. IWA Publishing.

[7] Plappally, A. K., & Lienhard, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. Renewable and Sustainable Energy Reviews, 16(7), 4818-4848.

[8] UN Water. (2021). Sustainable Development Goal 6: Synthesis report on water and sanitation. United Nations.

[9] WHO. (2019). Drinking-water. World Health Organization.

[10] Bolton, J. R., & Cotton, C. A. (2008). The ultraviolet disinfection handbook. American Water Works Association.

[11] Bolognesi, A., Bragalli, C., & Lenzi, C. (2020). Energy efficiency in water supply systems: A review of optimization methods. Water, 12(5), 1356.

[12] Cath, T. Y., Childress, A. E., & Elimelech, M. (2013). Forward osmosis: Principles, applications, and recent developments. Journal of Membrane Science, 281(1-2), 70-87.

[13] Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: Energy, technology, and the environment. Science, 333(6043), 712-717.

[14] EPRI. (2012). Water and sustainability: U.S. electricity consumption for water supply and treatment—The next half century. Electric Power Research Institute.

[15] Gude, V. G. (2016). Desalination and sustainability—An appraisal and current perspective. Water Research, 89, 87-106.

[16] IEA. (2020). World energy outlook 2020. International Energy Agency.

[17] Olsson, G. (2012). Water and energy: Threats and opportunities. IWA Publishing.

[18] Plappally, A. K., & Lienhard, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. Renewable and Sustainable Energy Reviews, 16(7), 4818-4848.

[19] Rosso, D., Larson, L. E., & Stenstrom, M. K. (2008). Aeration of large-scale municipal wastewater treatment plants: State of the art. Water Science and Technology, 57(7), 973-978.

[20] Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., & Marinas, B. J. (2008). Science and technology for water purification in the coming decades. Nature, 452(7185), 301-310.

[21] Voutchkov, N. (2018). Energy use for membrane seawater desalination—Current status and trends. Desalination, 431, 2-14.