DOI: 10.31276/VJSTE.2024.0062

Energy efficiency evaluation of a centralised wastewater treatment plant in an industrial zone of former Binh Duong province, Vietnam

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Received 2 November 2024; revised 30 December 2024; accepted 26 February 2025

Abstract:

Efficient energy utilisation in wastewater treatment plants is a significant challenge for management, particularly in developing countries. This study presents an integrated approach combining energy auditing, real-time monitoring, and energy assessment to optimise industrial wastewater treatment plant operations in Vietnam, with a treatment capacity of under 4,000 m³/day. The research methodology employs an energy audit approach combined with daily measurements, analysing the plant's operational data for 2023. Results indicate that the aerobic tank consumes the most energy (56.1% of total plant consumption). Wastewater pumps, blowers, mixers, and sludge pumps consume a substantial amount of electricity (77.6% of total electricity consumption). The average specific energy consumption is 0.93 kWh/m³ of treated wastewater, 10.58 kWh/kg $COD_{removed}$, and 59.12 kWh/kg $TN_{removed}$, which are 15-20% higher than international benchmarks for similar-scale facilities. Based on the analysis, we propose optimisation strategies: (1) improving operating conditions and flexibility; (2) optimising the blower system for aerobic tanks; (3) upgrading to energy-efficient pumps; (4) enhancing lighting, automatic monitoring, and office systems; (5) integrating renewable energy sources. These interventions could reduce energy consumption by 25-30% while maintaining treatment efficiency. The research findings will enhance the plant's energy efficiency, reduce operational costs, and support Vietnam's goal of achieving net-zero emissions by 2050.

Keywords: **electricity consumption, energy audit, energy efficiency, industrial wastewater, specific energy consumption, wastewater treatment.**

Classification numbers: **2.1, 2.3, 5.3**

1. Introduction

Energy consumption costs in wastewater treatment plants (WWTPs) are a major concern for managers. Research indicates that water treatment is an energy-intensive process in the water industry. In the United States, energy consumption for urban wastewater treatment accounts for 3% of total residential electricity demand, and approximately 5% in several other countries worldwide [1]. Electricity expenditures account for 25-40% of operational costs for WWTPs [2, 3], with over 50% of energy demand utilised for aerobic processes [4, 5]; 10-20% for pumps; and 35% for sludge treatment, sludge dewatering, and auxiliary equipment [6]. The expense of managing and treating wastewater alone constitutes 0.06% of GDP in the European Union [7]. Energy consumption in urban water supply systems is predicted to increase by 60-100% in the future [8], not only causing resource waste but also contributing to increased greenhouse gas emissions, global climate change, and other environmental issues.

Finding solutions for efficient energy use in WWTPs is urgent and can help reduce electricity costs by 10-20%, with some plants achieving up to 50% reduction [9]. A study by D. Panepinto, et al. (2016) [10] of the Castiglione plant in Italy showed that optimising the primary settling tank can save 25% of electricity consumption, and 20-36% for the aerobic tank through automatic control of dissolved oxygen (DO) concentration and sludge retention time (SRT). Energy savings of 29% were achieved when adjusting the DO set point to optimal conditions in the aerobic tank [11]. W.Y. Sean, et al. (2020) [12] studied energy optimisation by simulating energy consumption in WWTPs combined with the supervisory control and data acquisition (SCADA) system, showing potential 20% energy demand savings.

Energy savings can be achieved through upgrading and improving treatment systems, maintaining equipment and machinery, and optimising auxiliary processes [13]; or recovering renewable energy to serve the wastewater treatment system and control the aerobic activated sludge

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process [14]. Using energy auditing tools and energy management according to ISO 50001 standards shows that energy savings can reach 5-10% through repairing existing pumps, 30% through maintenance and appropriate power adjustment, 20-50% through optimising technological parameters, and 30% energy efficiency through applying medium-temperature anaerobic decomposition with substrate addition for sludge treatment [9, 15]. Research findings from 23 WWTPs in Europe indicate that Germany can save 50% of power, while Switzerland has the potential to save 38% [6]. These global research results demonstrate that various solutions can achieve energy savings in WWTPs.

In Vietnam, research on WWTP energy efficiency has been limited. M. Sabelfeld, et al. (2022) [11] analysed energy optimisation potential in two industrial WWTPs, finding that dissolved oxygen control optimisation could reduce energy consumption by 29%. Research on the overall energy consumption of industrial WWTPs is still limited, especially for small and medium-sized plants. This study addresses this gap by providing a detailed energy consumption analysis and practical optimisation solutions.

The centralised My Phuoc 1 WWTP (MP1), located in My Phuoc industrial park, former Binh Duong province, was selected as the research subject. This industrial park plays a crucial role in former Binh Duong province's economy. The plant currently receives wastewater from 86 enterprises with various production types. Although the MP1 was built in 2017 and upgraded in 2021 to enhance wastewater treatment efficiency, the plant's energy efficiency has not yet been studied.

2. Materials and methods

2.1. Study area

The MP1 is located in My Phuoc 1 industrial park, one of former Binh Duong province's multi-sector industrial zones. The park benefits from its strategic location within the southern key economic quadrangle, which includes former Ho Chi Minh City, former Binh Duong province, former Dong Nai province, and former Ba Ria - Vung Tau province. This advantageous positioning has attracted numerous enterprises to invest and operate in the area. The MP1 WWTP was initially constructed in 2017 and underwent renovation and upgrades in 2021 to ensure compliance with centralised wastewater treatment requirements. The plant has a designed capacity of 4,000 m^3/day. Currently, it receives wastewater from 86 diverse industrial enterprises, encompassing various production sectors such as paper, textiles, leather and footwear, metallurgy, food processing, packaging production, mechanics, and electronics. The plant operates at an average capacity of 2,500-3,000 m^3/day. The influent wastewater is required to meet the Vietnamese standard technical regulations (QCVN), QCVN 40:2021/BTNMT, column B, while the effluent wastewater must comply with QCVN 40:2011/BTNMT, column A (with coefficients kq=0.9 and kf=0.9). Fig. 1 illustrates the schematic diagram of the treatment process in MP1.

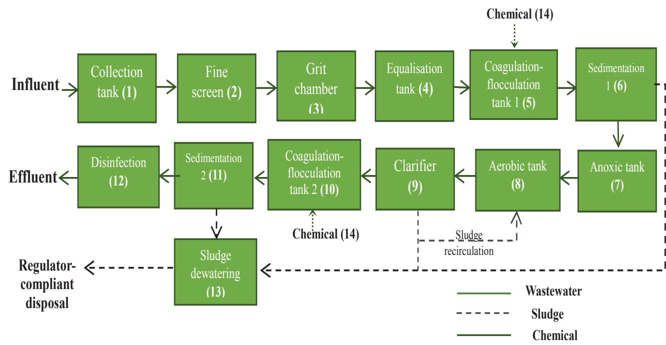

Fig. 1. Schematic diagram of the treatment process in MP1.

2.2. Data collection

Data were collected through direct measurements of electrical devices, technical specifications of each device, and operations. An electrical measurement diagram was utilised. Additional data were obtained from power bills. Daily data were acquired through the SCADA system and automatic monitoring system, including wastewater flow, influent, and effluent wastewater concentrations. The research period spanned from January to December 2023. Data analysis was conducted using Microsoft Excel and Origin Pro 2024 software.

2.3. Measurement equipment

The following equipment was used for measurements: a Kyoritsu clamp meter (model K2200) with accuracy of ±2.0% for current measurements (range: 0-1000A) and ±1.5% for voltage measurements (range: 0-600V); a thermometer (model GM53) with accuracy of ±0.5°C (range: -50 to 300°C); an Endress Hauser flow meter with accuracy of ±0.5% of measured value; a SCADA system; and a monitoring system.

2.4. Research methods

The research methodology framework comprised three steps: (1) Measuring, calculating, and analysing the entire plant's electricity demand; (2) Assessing the plant's energy use efficiency; and (3) Proposing solutions to save energy and improve the plant's operating conditions.

2.4.1. Measurement, calculation, and analysis of the entire plant's electricity demand

Electricity consumption for each device was measured and analysed. Energy consumption indices for each device were calculated using the following equation [10]:

$$A = P \times t \quad (1)$$

where A is amount of electricity consumed in time t (kWh/day), P is the absorbed power of each device (kW); and t is the operation time (h/day).

The absorbed power of each device was calculated using the following equations [10]:

$$P = U \times I \times \cos\varphi \text{ (one-phase systems)} \quad (2)$$

$$P = \sqrt{3} \times U \times I \times \cos\varphi \text{ (three-phase systems)} \quad (2')$$

where P is the absorbed power of each device (kW), U is the voltage (V), I is the average current absorption of each device (A), table 1 and cosφ is the power factor for each device (in case the device does not have one, the cosφ factor is obtained from the technical information provided by the equipment supplier). In a few cases, P was directly measured using a clamp meter.

2.4.2. Evaluation of the energy performance of the MP1 WWTP

The distribution of electrical energy use throughout the plant was analysed to determine the most energy-consuming stages. An operational survey was conducted to evaluate the relationship between power consumption and the operating process. The specific energy consumption (SEC) index was

Table 1. The electrical equipment used in the MP1 wastewater treatment plant.

Unit	Equipment	Quantity	Operating hours* (h/day)	Power consumption* (kWh/day)	Description
Collection tank	Pump	2	12	180	The pumps operate alternately
Fine screen	Fine screen	1	12	9	Operates according to the influent wastewater pump
Grit chamber	Sand pump	1	0.5	0.3	Manual operation when chamber is full
Equalisation tank	Wastewater pump	2	7	23.8	Alternating operations
	Frequency converter	1	14	10.5	Operates according to the operation of equalisation tank
	Stirrer	2	7	46.2	Alternating operations
Coagulation-flocculation tank 1	Mixer	2	14	30.8	Operates according to the operation of equalisation tank
Sedimentation tank 1	Scrapers	1	21	7.8	Independent activity, 2 hours of work, 15 minutes of rest
	Pump	2	12	36	Alternating operations
Anoxic tank	Mixer	4	12	158.4	Alternating operations
Aerobic tank	Blower	2	12	540	Alternating operations
	Blower	2	12	336	Alternating operations
	Frequency converter	2	12	18	Alternating operations
	Pump	4	12	264	Alternating operations
Clarifier	Scrapers	1	21	8.4	Independent activity, 2 hours of work, 15 minutes of rest
	Pump	2	12	141.6	Alternating operations
	Pump	1	2	3.4	Operates independently
Coagulation-flocculation tank 2	Mixer	3	14	46.2	Operates according to the operation of equalisation tank
Sedimentation tank 2	Scrapers	1	21	7.8	Independent activity, 2 hours of work, 15 minutes of rest
	Pump	2	2	6	Alternating operations
Disinfection	Pump	2	7	5.2	Alternating operations
Sludge dewatering	Pump	2	1	3	Rotating activities (4 hours/day)
	Scrapers	1	21	4.2	Independent activity, 2 hours of work, 15 minutes of rest
	Pump	2	2	6	Operates when sludge is present
	Sludge conveyor	1	4	6	Operates when sludge is present
Chemical pumping house	Pump	12	7	31.1	Alternating operations
		5	0.5	1	Operates 0.5 hours/day
Lighting, monitoring, office cluster	Automated monitoring station	1	24	36	Operates continuously 24/7
	Air conditioner	4	24	134.4	Operates continuously 24/7
	Lighting	13	12	6.2	
Total				2,107.2	

*Period of survey and measurement: From October to December 2023.

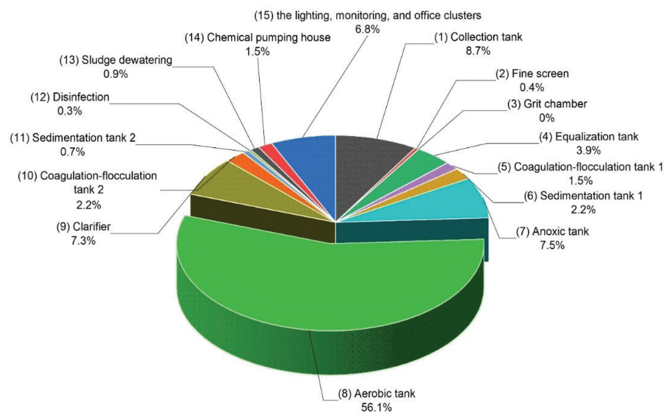

Fig. 2. Energy consumption of each unit.

calculated and expressed per cubic meter (kWh/m^3), per unit of chemical oxygen demand (COD) removed (kWh/kg $COD_{removed}$), and per unit of total nitrogen (TN) (kWh/kg $TN_{removed}$) [16, 17].

As the flow (Q) and concentration of input wastewater directly influence electricity consumption and fluctuate daily and throughout the year, the power consumption was evaluated based on the average monthly flow and the average monthly removed COD and TN concentrations [18, 19] (Eq. (3)). The removed COD and TN concentrations were calculated based on the input and output COD and TN concentrations (Eqs. (4) and (5)) [4, 17].

$$\text{SEC Q}\left(\frac{\text{kWh}}{\text{m}^3}\right) = \frac{\text{Average energy consumption (kWh/month)}}{\text{Average wastewater flow (m}^3\text{/month)}} \quad (3)$$

$$\text{SEC COD}_{\text{removed}}\left(\frac{\text{kWh}}{\text{kg}}\right) = \frac{\text{Average energy consumption (kWh/m}^3\text{)}}{\text{COD}_{\text{removed}}\text{ (kg/m}^3\text{)}} \quad (4)$$

$$\text{SEC TN}_{\text{removed}}\left(\frac{\text{kWh}}{\text{kg}}\right) = \frac{\text{Average energy consumption(kWh/m}^3\text{)}}{\text{TN}_{\text{removed}}\text{ (kg/m}^3\text{)}} \quad (5)$$

2.4.3. Proposal of solutions

Based on the results of the WWTP's energy performance evaluation, the study proposes solutions for the plant to improve operating conditions to optimise energy use and minimise costs.

3. Results and discussion

3.1. Allocation of electrical energy consumption in the plant

Measurement and calculation results indicate that, in 2023, the plant consumed an average of 75,330 kWh per month. Electricity costs accounted for 30% of the total wastewater treatment costs. Power consumption demand varied across different months (Fig. 2). Electricity consumption decreased in February, with peak usage occurring from March to September. This pattern can be attributed to the Vietnamese traditional Tet holiday at the end of January and in February, during which factories are less active, resulting in reduced wastewater flow. Additionally, February is typically when the plant conducts maintenance on the wastewater treatment system equipment, Fig. 2 leading to reduced operating time compared to normal operating months.

According to Table 1, on average, the entire plant consumed 2,107.2 kWh/day, corresponding to an average wastewater flow of 2,647 m³/day. The electrical energy consumed solely for the wastewater treatment system was 1,930.6 kWh/day, equivalent to 91.6% of the plant's total electrical energy consumption. The remaining electricity was utilised for lighting, offices, security, and other ancillary purposes.

The current operating capacity is 66.2% of the plant's design capacity of 4,000 m³/day.

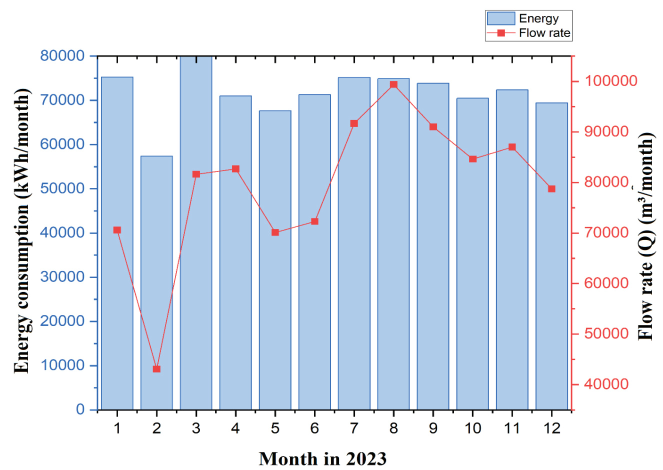

Fig. 3. The plant's energy consumption and wastewater flow in 2023.

The plant comprises 15 different energy-consuming units, with variations in energy consumption based on each unit's function, operating mode, and processing requirements. The aerobic tank is the highest energy consumer, accounting for 56.1% of total energy use. This underscores the aerobic tank's significant energy consumption within the entire WWTP. Other units that consume substantial amounts of energy include the collection tank, the anoxic tank, the secondary clarifier tank, and the lighting, monitoring, and office clusters (Fig. 3). The system of wastewater pumps, blowers, mixers, and sludge pumps consumes 1,634.6 kWh/day, equivalent to 77.6% of total electricity consumption. These systems present significant energy optimisation potential if improved and upgraded.

A comparison of the energy allocation results for each treatment unit at the MP1 WWTP with general information on energy consumption in the wastewater treatment sector reveals that the MP1 plant's aerobic tank energy consumption rate (56.1%) is comparable to other studies, where aerobic treatment processes typically consume more than 50% of the energy demand. However, the electricity consumption rate for the pump system, blower, mixer, and sludge pump at the MP1 plant (77.6%) is significantly higher than the average level of 10-20% reported in other studies, as mentioned in the reference documents (Table 2). Therefore, to optimise energy efficiency, the plant requires solutions to improve and upgrade components such as the aerobic tank, wastewater pump system, blowers, mixers, sludge pump, and lighting and monitoring cluster.

Table 2. Energy consumption of wastewater treatment plants in various countries.

Country	Aerobic treatment (%)	Pump (%)	Sludge treatment (%)	Other (%)	References
Greece	67.2	11	4.3	21	[2]
Germany	67	5	11	17	[20]
Finland	53	30	-	17	[21]
Italy	50	-	29	21	[10]
Portugal	54	-	13	33	[22]
Singapore	50	16	11.9	22.1	[23]
China	52	18	9	21	[24]

3.2. Evaluation of plant operations

The study conducted a survey of the plant's operations to evaluate the relationship between electricity consumption and the operating process. The results indicate that, although the processing line is operated automatically through the SCADA system with pre-programmed algorithms to support operational optimisation, some installed equipment operates continuously regardless of wastewater treatment flow (Table 1). To ensure microbial sludge activity, aerobic and anoxic tanks must maintain continuous operation. Similarly, sludge scrapers in sludge compression tanks, biological clarifier tanks, and sedimentation tanks also require continuous operation to avoid sludge decomposition and floating on the surface, which could affect treatment efficiency. This continuous operation is one of the factors affecting energy use efficiency, with the energy consumption for these units being 1,336.2 kWh/day, accounting for 63.4% of the total energy consumption of the entire factory (2,107.2 kWh/day).

The research findings also reveal that the power consumption of the plant is concentrated in the aerobic biological tank. Although the treatment results consistently meet the discharge standards QCVN 40:2011/BTNMT, column A (kq=0.9; kf=0.9) (Fig. 4), the tank's power consumption reaches 1,158 kWh/day, accounting for 56.1% of the plant's total power consumption (2,107.2 kWh/day).

Dissolved oxygen (DO) concentration has been identified as an important parameter in determining treatment efficiency and electricity usage efficiency. Controlling DO concentrations presents significant energy optimisation potential. The investigation and survey results indicate that the plant currently maintains an average DO concentration in the range of 2-3.5 mg/l. However, a DO concentration of 2.0 mg/l has been found to be sufficient for aerobic, including nitrification [25]. Consequently, a reduction in aeration concentration could potentially reduce power consumption by 30%, equivalent to 662 kWh/day in energy savings.

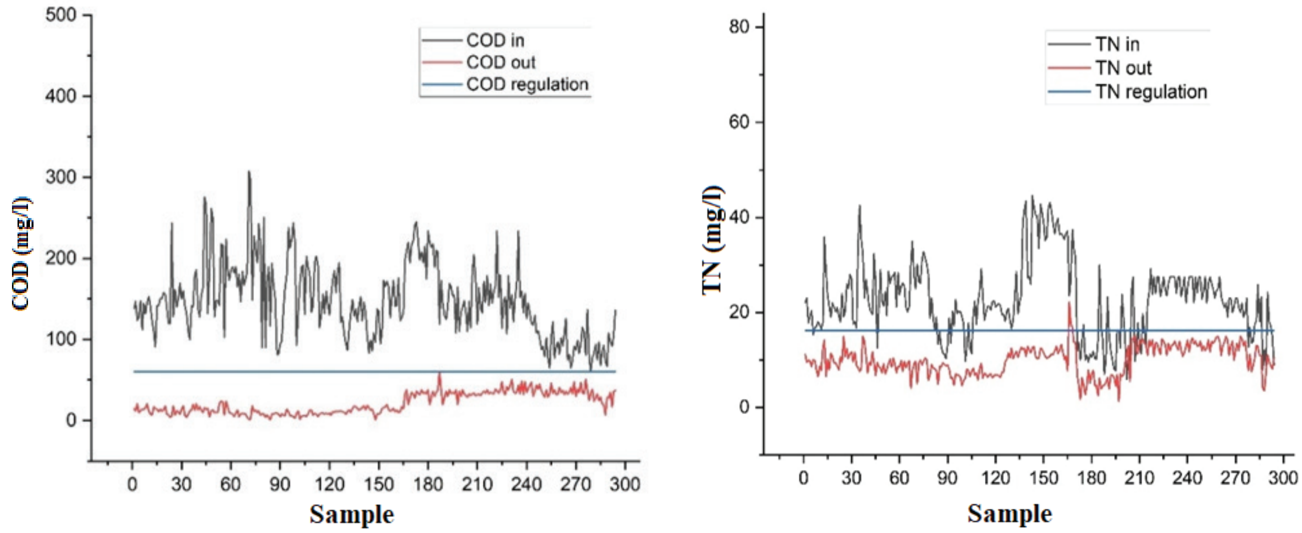

Fig. 4. Input and output chemical oxygen demand and total nitrogen concentrations in 2023.

3.3. Energy efficiency assessment of wastewater treatment plants

3.3.1. Energy use efficiency is calculated per cubic meter (m³) of treated wastewater

The combination of results from Table 1 and the SEC calculated using Eq. (3) indicates that the SEC for the entire MP1 WWTP in 2023 is 0.93 kWh/m³ (Fig. 5).

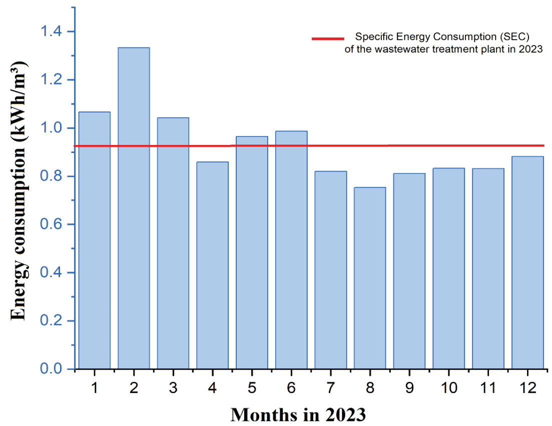

Fig. 5. Energy consumption by month.

Statistical analysis reveals that the average energy consumption of the MP1 WWTP is significantly higher than that of other plants worldwide using the same activated sludge technology (Table 3). These findings suggest that the MP1 WWTP is currently operating at suboptimal energy efficiency. It is imperative to implement energy-saving strategies and optimise energy efficiency to comply with international standards and best practices in the wastewater treatment industry.

Table 3. Specific energy consumption (SEC) of MP1 compared to wastewater treatment plants in other countries.

Plant	SEC (kWh/m³)	References
MP1	0.93	Current study
Europe	0.15-0.7	[8]
United States	0.33-0.60	[26]
Australia	0.46	[8]
China	0.269	[27]

3.3.2. Energy efficiency per kg chemical oxygen demand and total nitrogen removed

To evaluate the WWTP's treatment efficiency, the study conducted daily sampling of influent and effluent from January to December 2023 (totalling 294 sampling events) to evaluate the treatment efficiency of the WWTP. Although the effluent COD and TN concentrations met the discharge standards according to QCVN 40:2011/BTNMT, column A (regulated COD: 60.75 mg/l, regulated TN: 16.2 mg/l), the analysis results indicate that the treatment efficiency of the WWTP was suboptimal and inconsistent. The COD removal efficiency fluctuated between 83 and 88%, while the TN removal efficiency ranged from 53 to 55% (Fig. 4).

The SEC for removing 1 kg of COD varied from 6.31 to 15.87 kWh/kg $COD_{removed}$, with an average SEC of 10.58 kWh/kg $COD_{removed}$. The SEC for removing 1 kg of TN ranged from 23.23 to 126.02 kWh/kg $TN_{removed}$, with an average SEC of 59.12 kWh/kg $TN_{removed}$ (Fig. 6). These values are substantially higher than the current industry averages of 0.3-2.2 kWh/kg $COD_{removed}$ and 2.2-6.9 kWh/kg $TN_{removed}$ [15, 28]. The energy efficiency evaluation results (Fig. 6) demonstrate that in July, when influent COD and nitrogen concentrations peaked, the specific energy consumption was at its lowest. This suggests that energy efficiency reaches optimal levels at high COD and nitrogen concentrations. In the remaining months of the year, despite lower COD and nitrogen concentrations, the specific energy consumption was higher.

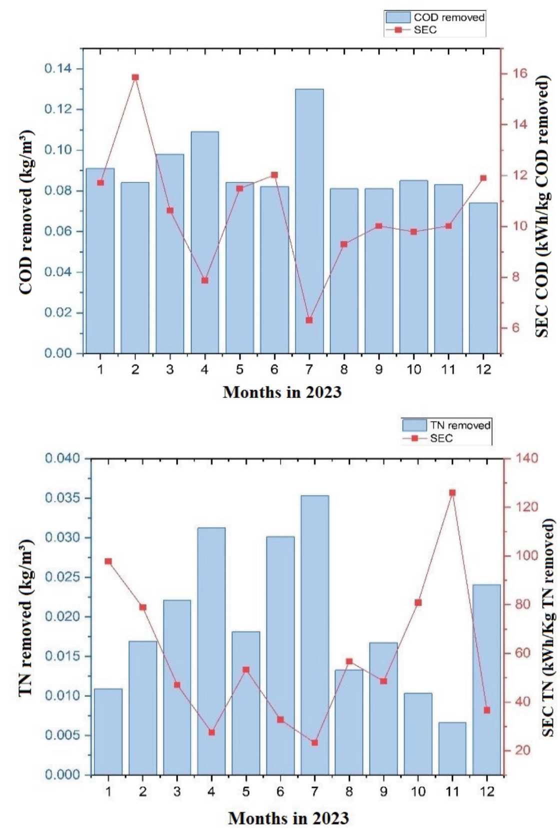

Fig. 6. Energy efficiency per kg chemical oxygen demand and total nitrogen removed.

Analysis of the operational modes of equipment in the MP1 WWTP (Table 1) reveals that most devices are set to operate in fixed modes, with minimal adjustments based on pollutant loads and influent wastewater flow. This leads to energy waste during periods of low load. Therefore, to optimise energy efficiency, the plant needs to implement solutions for more adaptive operational time adjustments, aligning with variations in influent pollutant loads and wastewater flow rates across different treatment stages.

3.4. Proposed effective energy-saving solutions for the MP1 wastewater treatment plant

3.4.1. Improve operating conditions and flexibility

The MP1 WWTP should implement a flexible operating program based on changes in actual load and wastewater flow. Establishing a central SCADA system to monitor operating parameters and make adjustments based on the actual load regime is recommended.

3.4.2. Optimise the blower system for aerobic tanks

To optimise blower operation, the plant needs to assess the blower system and air distribution equipment. To enhance oxygen transmission efficiency, the plant should upgrade the blower system with energy-saving technologies, such as small-hole diffuser air blower discs. This technology can potentially save 25% of electricity consumption. Implementing new technology and energy-optimised air blowers, such as magnetic suspension centrifugal blowers, could help the factory save energy by 15-24% [29].

The plant should optimise the DO set point to a level of 2.0 mg/l compared to the current set level of 2-3.5 mg/l. This adjustment could help the plant save 30% of energy (662 kWh/day). Irregular sensor maintenance and lack of cleaning can lead to erroneous online measurements that affect operational data. To ensure the accuracy of the DO probe, the plant must develop periodic calibration and cleaning plans. Proper maintenance of the DO sensor can help the plant reduce energy consumption by 7-9% [30].

To improve operating conditions in biological tank clusters, the application of simulation software such as The super model [31], Worldwide Engine for Simulation, Training and Automation [32] and General Purpose Simulator [33] can be considered to predict results in advance. Operating efficiency in different scenarios requires optimising sludge retention time (SRT), hydraulic retention time (HRT), and DO concentration to find suitable operating solutions while still ensuring cost-effectiveness.

To ensure optimal equipment operation, the plant must develop and adhere to maintenance schedules. Implementation of periodic monitoring programs is necessary to identify improvement opportunities. Simultaneously, the plant needs to establish sets of indicators to evaluate operating performance, such as the standard energy consumption index, operating energy consumption index, air blowing demand, pump performance, and seasonal operating times. Benchmarking energy usage against historical data or comparing with the design capacity of other manufacturers and factories with similar technology is recommended. Establishing these sets of indicators helps the factory better control electrical energy consumption.

3.4.3. Upgrade the pumping and mixing system

To optimise pump system operation, the plant should create detailed pump management records, including name, pump motor details, function, pressure head, speed, operating hours, consumption rate, and electrical power. Conducting pump operation investigations to optimise performance and build load curves is advised. The plant should develop a plan to periodically check pump performance, inspect the motor, or replace pumps with appropriate performance.

Enhancing pump operating conditions by repairing and upgrading pumps to suit actual requirements or combining pumps with more efficient motors to improve flow can help the plant save 5-10% of energy consumption [26].

Replacing or upgrading equipment using new energy-efficient technologies, such as pumps with frequency converters that match the flow rate, can help reduce energy needs. These solutions can potentially save energy consumption by 3-7% [26].

3.4.4. Improve lighting, automatic monitoring, and office systems

To minimise power consumption for lighting, automatic monitoring, and office systems, the plant needs to develop action programmes and effective energy use strategies such as awareness-raising programmes, energy-saving methods, implementing energy efficiency goals, and maintaining air conditioning at a stable temperature suitable for office functions.

For the entire air conditioning system, the plant should fully implement operating, maintenance, repair, and industrial cleaning regimes. These solutions can potentially help the plant save 3-5% of electricity.

To achieve the goal of sustainable development, the MP1 WWTP should implement energy management according to the ISO 50001 standard and research the potential of combining renewable energy sources to contribute to cost savings and improve environmental protection efficiency.

3.4.5. Integration of renewable energy sources

WWTPs can also offset their energy requirements by the integration of renewable energy sources such as solar, and biogas. Implementation of rooftop and ground-mounted photovoltaic systems at wastewater treatment facilities enables direct power generation for treatment equipment and auxiliary systems, reducing reliance on conventional energy sources while harnessing abundant solar resources as a sustainable alternative. Furthermore, the utilisation of treated sludge, particularly organic sludge, offers significant potential for biogas production and biofuel generation [15]. Research indicates that comprehensive renewable energy integration can satisfy up to 23% of facility energy demands while achieving a 15% reduction in emissions [34, 35]. This multi-faceted renewable energy strategy not only enhances energy independence but also contributes substantially to environmental sustainability objectives.

The implementation of these comprehensive strategies could reduce energy consumption by 25-30% while maintaining treatment efficacy. Success depends on critical factors including investment capital, technical expertise, maintenance capabilities, and operational conditions. Table 4 synthesises the key solutions, quantified energy savings, and implementation requirements, providing a strategic framework for energy efficiency enhancement at the WWTP.

Table 4. Summary of energy-saving solutions for wastewater treatment plant optimisation.

Solutions	Energy savings (%)	Implementation requirements
DO optimisation	30	Advanced DO sensors with SCADA system integration [30]
Blower system upgrade	15-25	High-efficiency diffusers, magnetic bearing blowers [29]
Pump system optimisation	5-10	Variable Frequency Drive (VFD) controllers, energy-efficient pumps [26]
Monitoring enhancement	20	Advanced SCADA system with IoT sensor network [12]
Renewable energy sources	23	Integration of solar, and biogas systems [34, 35]

4. Conclusions

This study presents a comprehensive energy efficiency analysis of an industrial wastewater treatment plant in Vietnam, providing valuable insights into energy consumption patterns and optimisation potential in small to medium-scale facilities. Through a systematic methodology combining energy auditing, real-time monitoring, and performance assessment, our research offers valuable insights into energy consumption patterns and optimisation potential. Key findings from the research include:

The MP1 WWTP, operating at 66.2% of its design capacity (2,647 m^3/day out of 4,000 m^3/day), demonstrates significant opportunities for energy optimisation. Energy audit results revealed that the aerobic process, particularly the aerobic tank, accounts for 56.1% of total plant consumption. The combined system of pumps, blowers, mixers, and sludge handling equipment consumes 77.6% of total electricity (1,634.6 kWh/day), substantially higher than international benchmarks.

Performance analysis indicated that the facility's specific energy consumption metrics-0.93 kWh/m^3 of treated wastewater, 10.58 kWh/kg $COD_{removed}$, and 59.12 kWh/kg $TN_{removed}$-exceed typical industry standards by 15-20%. This suggests considerable potential for energy efficiency improvements through targeted interventions in key processes.

Based on our analysis, we proposed practical optimisation strategies including DO control enhancement, blower system upgrades, and pump system optimisation that could potentially reduce energy consumption by 25-30% while maintaining treatment efficiency. The feasibility assessment shows that these solutions can be widely applied to similar WWTPs, especially those with treatment capacities of 2,000-4,000 m^3/day. Implementation success at other facilities would depend on available investment capital, technical expertise, maintenance capabilities, energy costs, and specific operational conditions.

The research findings emphasise the importance of systematic energy optimisation approaches in industrial wastewater treatment facilities. This study contributes valuable insights to support Vietnam's wastewater treatment sector in improving operational efficiency while working toward the national goal of achieving net-zero emissions by 2050. Study limitations suggest future research directions in optimisation simulation tools, long-term performance monitoring, renewable energy feasibility assessment, and solution adaptability across industrial sectors.

CRediT author statement

Vinh Thi Nguyen: Conceptualisation, Methodology, Data collection and analysis, Writing original draft; Le Hung Anh: Research oversight, Results and Discussion, Critical review, Manuscript finalisation; Trung Minh Dao: Methodology support, Data collection supervision, Manuscript review; Thang Anh Nguyen: Technical expertise, Data interpretation, Manuscript revision; Tan Thanh Le: Site access facilitation, Operational data provision, Results and Discussion.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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