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Review

Optimization of Energy Consumption in a Wastewater Treatment Plant: An Overview

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Abstract: Wastewater Treatment Plants (WWTPs) play a crucial role in maintaining ecological balance, a cornerstone of environmental health for thriving biodiversity and undisturbed natural processes. This balance is crucial for the sustainability of ecosystems, directly influencing human health, biodiversity, and the overall quality of our natural environment. WWTPs contribute to this equilibrium by efficiently removing pollutants and harmful substances from wastewater, thus averting the degradation of water bodies that are essential for numerous ecological processes. WWTPs encompass multiple stages of wastewater and sludge treatment and are significant energy consumers globally, especially in secondary treatment, particularly the activated sludge method which is the most common method. With an upcoming directive from the European Union aiming to reduce energy consumption in WWTPs, this paper focuses on a literature review examining global practices implemented across all stages of WWTP treatment processes. It summarizes the key points of each study, focusing primarily on the outcomes of each application. This document concludes with an in-depth review of each study and provides general conclusions for each group of studies. The objective is to identify methods that have effectively reduced energy consumption and enhanced the overall energy efficiency of WWTPs. The main conclusions indicate that the studies encompass a wide range of applications that achieve significant reductions in energy consumption. However, additional testing of these applications in more diverse operating environments through trials could further enhance their reliability and increase acceptance among WWTP operators.

Keywords: sewage treatment; energy efficiency; ecological balance; biodiversity; sustainability

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1. Introduction

The landscape of Wastewater Treatment (WWT) is undergoing significant change, moving towards a more integrated approach that emphasizes resource recovery and attaining net-zero carbon conditions. Wastewater treatment plants (WWTPs) play a crucial role in driving this shift, but they also contribute significantly to global greenhouse gas (GHG) emissions. The interconnectedness of water and energy is essential for sustainable development, as WWTPs require energy to mitigate their environmental impact. However, reliance on fossil fuel-based energy sources can worsen GHG emissions. To tackle this challenge, many countries have implemented energy-saving policies, prompting the WWT industry to develop technologies aimed at improving energy efficiency. Nevertheless, achieving energy self-sufficiency remains a complex challenge without a solution.

Traditionally, WWTPs have been designed primarily to meet effluent requirements with little consideration for energy consumption. As water scarcity rises, urban water systems increasingly rely on energy for conveyance and treatment. Furthermore, given the growing concerns about climate change, energy-saving measures have become essential worldwide. Despite their pivotal role in improving water quality, WWTPs frequently stand out as major energy consumers among municipal facilities. Therefore, optimizing energy usage in these plants is critical for both environmental sustainability and operational efficiency. This study offers a comprehensive review of various methodologies and strategies employed globally to decrease electrical energy consumption in WWTPs. It delves not only into the theoretical aspects [1–5], but also into practical applications [6–10], showcasing successful implementations.

The significance of energy conservation in WWTPs is underscored by an escalating need for sustainable practices amidst rising energy prices and mounting environmental concerns [11]. This study reveals several key aspects of novelty in the context of optimizing energy consumption and fostering sustainability within WWTPs, including integration of advanced technologies, comparative evaluation methods, significant energy reductions, flow modeling and simulation, growth models and scenario-based optimization, identification of critical barriers, energy self-sufficiency studies, dynamic optimization algorithms and renewable energy integration, and finally, future research directions. Overall, this review paper indicates that the novelty lies in the integration of advanced technologies, innovative modeling and simulation techniques, comparative evaluations, and the emphasis on future research directions aimed at enhancing the economic and practical applicability of these methods within the WWT sector. Through an exploration of successful case studies, this review seeks to contribute to the ongoing dialogue on sustainable wastewater management. Moreover, while acknowledging the significant global efforts to reduce energy consumption in WWTPs, this work encourages readers to think beyond the presented findings. The critical review of each study highlights the importance of considering potential challenges and limitations before adopting these methods. This careful consideration is crucial to avoid unforeseen developments that could disrupt the smooth operation of WWTPs, both economically and operationally. Ultimately, the integration of energy-saving methods not only minimizes the environmental impact of WWTPs but also positions these facilities as contributors to a more sustainable and resilient future [12,13].

2. Methodology

For the preparation of this article, a literature search was conducted covering the period from 2007 to 2023, uncovering numerous studies that either have been practically implemented or have developed theoretical models leading to potential reductions in energy consumption at WWTPs. Initially, over than 180 references were gathered. These 114 indexed scientific articles, technical reports, book chapters, and conference proceedings were chosen from databases like Science Direct, Web of Science, Google Scholar, PubMed, and Research Gate. The remaining references were excluded due to various reasons, such as insufficient research information provided, unreliable sources (e.g., student theses), or lack of scientific validity. In Table 1, the keywords and phrases (listed in the left column) used to find the references for this research are displayed. The right column indicates the number of references found using each specific keyword or phrase. Many of these keywords/phrases are associated with more than one reference.

The keywords/phrases are listed in descending order, with the first keyword being the most popular in the literature search conducted.

Significant efforts to reduce energy consumption have concentrated on the secondary treatment stage of WWTPs, particularly the aeration tank, where the activated sludge method is used. Additionally, energy-saving measures have targeted the pumping required between various processing stages and the stages of sludge processing. Subsequently, each study examined is presented with its central idea, accompanied by a succinct summary of the obtained results. Lastly, a critical review of the references under examination is provided, along with recommendations for future research.

In Figure 1, the number of references cited within this study in the section "WWT Technologies", and its subsections is displayed. We observe that there is an almost uniform distribution of references, with the majority being in the section that analyzes secondary treatment.

Table 1. The keywords/phrases used in this study, along with the corresponding number of references.

Keywords/Phrases	Number of References
Treatment stages of wastewater	33
Aeration energy optimization in WWTPs	22
Secondary treatment	22
Activated sludge treatment	18
Sustainable WWT practices	16
Energy recovery in WWT	16
Tertiary treatment in WWTPs	15
Energy-saving techniques in WWTPs	14
Energy optimization in WWT	12
Energy consumption at different stages of process	12
Renewable energy in WWTPs	12
Process optimization in WWTPs	11
Data-driven approaches for energy saving in WWTPs	11
Stage of sludge treatment	10
Carbon footprint reduction in WWTPs	9
Energy consumption reduction in WWTPs	8
Energy audit in WWTPs	8
Anaerobic treatment	7
Operational strategies for energy efficiency in WWTPs	7
Aerobic process	5
Biogas production during digestion	4
Preliminary treatment	4
Primary treatment	3

The color gradient in Table 1 represents the frequency of occurrence of each "Keyword/Phrase" in the literature search. The gradient follows a scale from green (highest frequency) to red (lowest frequency), with the most popular "Keyword/Phrase" at the top row and the least popular at the bottom row. The top row has 33 references, while the bottom row has 3 references.

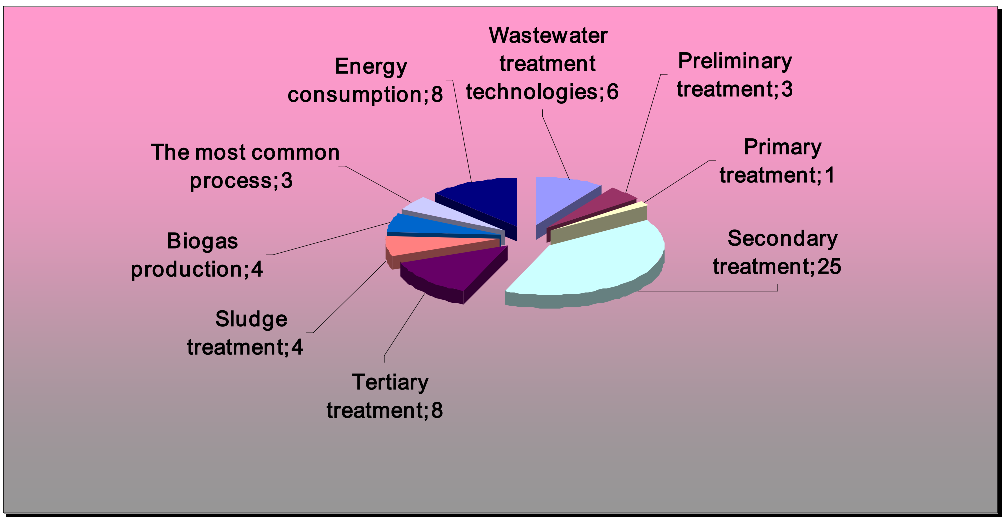

Figure 1. Distribution of references in the "WWT Technologies" section.

In Figure 2, the number of references per subsection within the "Overview" section is matched. Specifically, section "5. Overview" consists of the following subsections:

- 5.1. Energy optimization during aeration process;
- 5.2. Proposed methods to reduction in energy during sludge treatment;
- 5.3. Emphasizing multiple stages of WWT;
- 5.4. Modification in the operation of the pumps;

- 5.5. Addition of equipment and utilization of existing infrastructure;
- 5.6. Application of renewable energy sources;
- 5.7. Modeling individual processes in WWTPs;
- 5.8. Simulation for predicting energy consumption;
- 5.9. Comparative evaluation between various WWTPs;
- 5.10. Theoretical thermodynamic study;
- 5.11. Other case studies.

It is obvious that Section 5.1, which examines methods for reducing energy consumption during the aeration process, holds the top position, followed by Section 5.6, "Application of renewable sources".

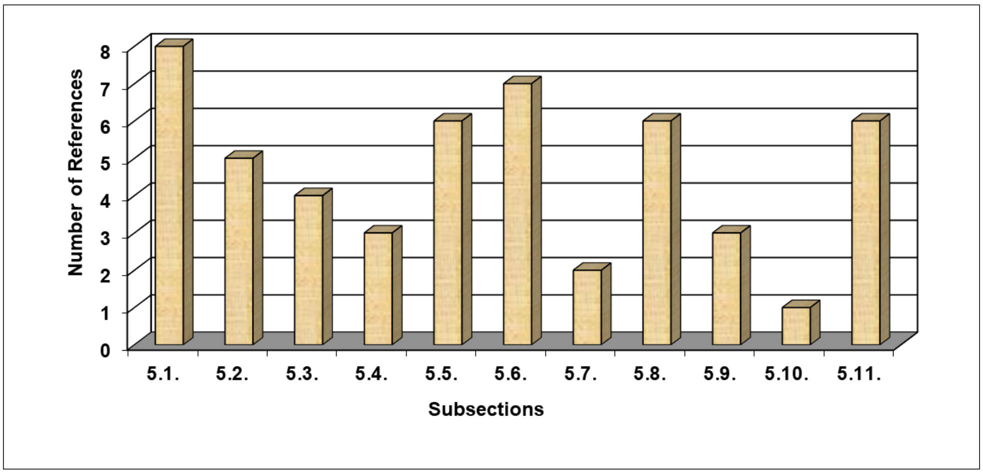

Figure 2. Separation of sources in the "Overview" section.

3. WWT Technologies

A sewage treatment facility plays a crucial role in managing both domestic and commercial waste by removing materials that could pose risks to public health. Its primary objective is to generate environmentally safe liquid waste, known as treated effluent, as well as solid waste, referred to as treated sludge, which can be safely disposed of or reused, often as fertilizer in agriculture [14]. Given the escalating environmental pollution, there is a growing imperative to study wastewater characteristics, especially for domestic sources, to effectively tackle the need for decontamination [15].

WWT is typically divided into four levels [16,17]:

- Preliminary
- Primary
- Secondary
- Tertiary

The purpose of preliminary treatment is to remove large solids, while primary treatment aims to eliminate settleable solids and some organic material. Physical mechanisms are primarily used at both levels for pollutant removal. In secondary treatment, the focus shifts to removing organic material and, potentially, nutrients (nitrogen and phosphorus) primarily through biological means (Table 2). Tertiary treatment is designed to remove specific pollutants, typically toxic or non-biodegradable compounds, or to supplement pollutants removal inadequately addressed in secondary treatment. Tertiary treatment is not commonly implemented in developing nations [18,19].

Table 2. Attributes of the main stages of wastewater treatment (modified from Kulkarni, [18]).

	Treatment Level (1)		
Object	**Preliminary**	**Primary**	**Secondary**
Pollutants eliminated	Coarse solids	Settleable solids Particulate BOD *	Non-settleable solids Fine particulate BOD * Soluble BOD * Nutrients (3) Pathogens (3)
Treatment effectiveness	–	SS **: 60–70% BOD *: 25–40% Coliforms: 30–40%	SS **: 65–95% BOD *: 60–99% Coliforms: 60–99% (4)
Predominant treatment mechanism	Physical	Physical	Biological
Complies with usual discharge standards (2)	No	No	Generally, yes
Implementation	Upstream of pumping stations Initial treatment stage	Partial treatment Intermediate stage of a more complete treatment	More comprehensive treatment (for organic matter)

(1) At a secondary level WWTP, preliminary treatment is typically included, but the presence of primary treatment depends on the specific process employed. (2) The discharge standards outlined in legislation are subject to potential adjustment by the environmental agency. They may authorize alternative values if environmental studies indicate that the receiving body can accommodate a higher pollutant load. (3) Depending on the process, nutrients and pathogens can be eliminated or reduced during the secondary stage of treatment, contingent upon the treatment process utilized. (4) Including a specific removal stage can increase the efficiency of coliform removal. * BOD: Biochemical Oxygen Demand. ** SS: Suspended Solids.

3.1. Preliminary Treatment

The preliminary treatment [20] of wastewater encompasses crucial steps aimed at ensuring the effective operation of subsequent treatment processes [21,22].

1. Collection Systems: Proper planning of collection systems is crucial, necessitating analysis of population and flow projections. Designs should incorporate long-term growth patterns and water consumption data to effectively accommodate future expansions;
2. Screening: The removal of debris such as rags and plastic is essential to prevent equipment damage. Screening methods can be either manual or mechanical, but ensuring the proper disposal of removed waste is crucial to prevent health hazards and odors;
3. Grit Removal: Grit, comprising sand and small stones, can cause mechanical equipment damage if left untreated. Grit removal protects pumps and equipment from abrasion, ensuring smooth operation;
4. Comminution: Solid materials are reduced in size through processes like crushing or grinding to facilitate downstream treatment processes;
5. Disposal of Screenings and Grit: Proper disposal of screenings and grit is paramount to avoid odor and hygiene issues. Suitable containers with lids are utilized for disposal, and in smaller plants, burial in trenches is an option, followed by prompt covering with soil to prevent odors and pests.

Overall, effective preliminary treatment safeguards downstream treatment processes' integrity, minimizes equipment damage, and maintains hygienic conditions in WWTPs.

3.2. Primary Treatment

Primary treatment [18] in WWTPs is primarily focused on eliminating settleable suspended and floating solids. Even after undergoing preliminary treatment, sewage still contains fine suspended solids, predominantly organic matter. Sedimentation units are deployed to partially eliminate these suspended solids, thereby reducing the BOD load directed to secondary treatment, which is a more costly option. Sedimentation tanks, whether circular or rectangular, facilitate the settling of suspended solids as sewage flows slowly through them. The accumulated solids at the bottom, known as raw primary sludge, are removed via pipes or mechanical scrapers and pumps. Floating materials such as grease and oil rise to the tank's surface and are gathered for further treatment. Coagulants, such as aluminum sulphate or ferric chloride, can enhance the efficiency of primary treatment through a process known as Chemically Enhanced Primary Treatment (CEPT). Additionally, phosphorus removal via precipitation is feasible with this method. However, the use of coagulants results in increased sludge production due to the higher solids removal and chemical addition [23].

3.3. Secondary Treatment

Table 3 provides a summary of the primary secondary-level treatment systems [18] utilized for domestic sewage. Although wastewater treatment technology comprises numerous other processes and variations, the table below focuses on the most used systems in warm-climate regions.

Table 3. Summary of the primary biological WWT systems.

Stabilization Ponds [24–27]	
Facultative pond	Wastewater flows continuously through a purpose-built pond, where aerobic stabilization of soluble and fine particulate BOD occurs due to dispersed bacteria. Algae aid in oxygen provision through photosynthesis, but extensive land usage is required.
Anaerobic pond–facultative pond	Approximately 50 to 65% of BOD is converted in the deeper, smaller-volume anaerobic pond, with the remaining BOD eliminated in the facultative pond, requiring less space than a single facultative pond.
Facultative aerated lagoon	Like a facultative pond, but mechanical aerators provide oxygen instead of relying on photosynthesis. Despite aeration, settling of sewage solids and biomass occurs, decomposing anaerobically at the pond bottom.
Completely mixed aerated lagoon sedimentation pond	Thorough mixing keeps solids dispersed, enhancing BOD removal efficiency. Effluent contains elevated solids levels, necessitating removal before discharge into the receiving body, facilitated by a sedimentation pond.
High-rate ponds	Engineered to maximize algal production in a fully aerobic environment, with shallower depths allowing extensive light penetration, promoting photosynthetic activity and elevated oxygen levels. Moderate agitation is induced by low-power mechanical equipment.
Maturation ponds	Designed to eradicate pathogenic organisms by establishing unfavorable environmental conditions, such as exposure to UV radiation, high pH levels, abundant oxygen, lower temperatures, nutrient scarcity, and predation by other organisms. They serve as a post-treatment phase, demonstrating exceptional efficiency in removing coliforms.
Land Disposal [28–31]	
Slow-rate system	Involve dispersing wastewater onto the soil, aiming for either treatment or water reuse for agriculture or landscaping. Plants absorb liquid efficiently, even with minimal application on their surfaces. Various distribution methods are used, including sprinklers and drip irrigation.
Rapid infiltration	Distribute wastewater over shallow basins, allowing it to seep into the soil. Evaporation losses are minimized, and vegetation may or may not be cultivated. Application is intermittent, with options like groundwater recharge and underdrain recovery.
Subsurface infiltration	Involves introducing pre-treated sewage beneath the soil surface, often from septic tanks. Infiltration trenches or chambers aid conveyance and partial treatment before infiltration.
Overland flow	Overland flow systems disperse wastewater across vegetated slopes, with treatment occurring within the root–soil system. Distribution methods include sprinklers and pipes, with sporadic application.
Constructed wetlands	They are aquatic-based systems with shallow basins or channels supporting aquatic plants. Processes occur within the root–soil system, with options for free-water surface or subsurface flow configurations.

Table 3. *Cont.*

Anaerobic Systems [32–38]	
Upflow anaerobic sludge blanket reactor (UASB)	Employs anaerobic conversion of BOD by dispersed bacteria, with liquid flowing upwards. Methane is produced, and the reactor includes settling and gas collection zones. Minimal sludge production occurs, and excess sludge is already thickened and stabilized.
Anaerobic filter	In the anaerobic filter, organic pollutants are transformed by bacteria attached to a support medium within the submerged tank. A primary sedimentation tank is required, but sludge production remains minimal.
Anaerobic reactor–post-treatment	Anaerobic reactors often require post-treatment to meet discharge standards. This can involve biological or physical–chemical methods, with overall efficiency comparable to untreated wastewater but with reduced land, volume, and energy requirements, as well as lower sludge production levels.
Activated Sludge [39–43]	
Conventional activated sludge	Conventional activated sludge involves an aeration tank and a secondary sedimentation tank. Biomass is recirculated to maintain high concentrations for effective BOD removal. Excess sludge is treated for stabilization. Oxygen is introduced through mechanical aerators or diffused air.
Activated sludge (extended aeration)	Extended aeration extends the retention time of biomass, reducing substrate availability and promoting self-maintenance. Excess sludge is already stabilized, and primary sedimentation tanks are typically omitted.
Intermittently operated activated sludge (sequencing batch reactors)	Sequencing batch reactors operate intermittently, cycling between aerated and settling stages within one tank. Secondary sedimentation tanks are not needed, and the system can function in conventional or extended aeration modes.
Activated sludge with biological nitrogen removal	Includes an anoxic zone where nitrates serve as a respiratory substrate for microorganisms, reducing them to gaseous nitrogen.
Activated sludge with biological nitrogen and phosphorus removal	Activated sludge, featuring biological nitrogen and phosphorus removal capabilities, incorporates aerobic, anoxic, and anaerobic zones. Microorganisms absorb excess phosphorus, which is effectively removed with excess sludge.
Aerobic Biofilm Reactors [44–48]	
Low-rate trickling filter	Low-rate trickling filters facilitate aerobic stabilization of organic pollutants with bacteria adhering to support media. Sewage is distributed onto the tank's surface, filtering through the medium as bacteria degrade organic matter. Sludge dislodged from the medium is removed in a secondary sedimentation tank, and primary sedimentation is essential for effective operation.
High-rate trickling filter	High-rate trickling filters handle higher BOD loads, requiring sludge stabilization during treatment. Effluent recirculation to the filter dilutes influent and ensures consistent hydraulic load.
Submerged aerated biofilter	Submerged aerated biofilters contain porous material through which sewage and air flow continuously. Air moves upwards while liquid flow can be upward or downward. Granular material acts as a support and filter medium, removing soluble organic compounds and particulate matter. Periodic backwashings remove excess biomass, reducing head loss.
Rotating biological contactor (biodisc)	The biomass attaches to a support medium, typically consisting of a series of discs. These discs, partially submerged in the liquid, rotate and alternate between exposure to the liquid and air as they rotate.

3.4. Tertiary Treatment

Tertiary treatment [20] involves several methods aimed at further refining wastewater. These methods include: Constructed wetlands, Ecosystem technologies, Chlorination, Ozonation, UV radiation, and Maturation ponds:

1. Constructed wetlands [49,50]: These artificial wetlands use granular material to facilitate effluent flow, with reeds planted on the surface. They effectively remove inorganic nutrients, process organic waste, and reduce suspended sediments. Wetland

configurations include surface and subsurface flow, catering to different climatic conditions [51];
2. Ecosystem technologies: Inspired by natural ecosystems, these technologies replicate hydrological and mineral cycles. Living machines assemble organisms tailored to project goals, mimicking natural processes for effective water treatment [20];
3. Chlorination: Chlorine disinfection [52,53], in various forms, is a common method for water and wastewater treatment. Proper dosing is crucial to avoid ecological harm or health risks. Discharging into wetlands mitigates ecological risks, while strict adherence to safety protocols is essential;
4. Ozonation: Ozone disinfection [20], favored for its quick action and on-site production, requires proper dosage, mixing, and contact time for effective pathogen removal. Pilot testing and calibration ensure system efficiency before installation;
5. UV radiation: UV disinfection [54], though less common, relies on factors like effluent transmissivity and radiation intensity for microbial inactivation;
6. Maturation ponds: These ponds refine effluents, improving bacteriological quality and serving as buffers during operational disruptions. Proper maintenance minimizes nuisances and promotes plant growth, necessitating management measures. Specific directives ensure discharged effluent meets quality standards [55,56].

3.5. Sludge Handling

The WWT process consists of two essential components: the liquid phase and the solid phase, both equally significant. Wastewater sludge [20] can originate from various sources:

1. Raw or primary (from primary settling tanks);
2. Anaerobically digested;
3. Oxidation pond;
4. Septic tank;
5. Waste activated (sludge wasted from an activated sludge plant);
6. Humus tank;
7. Composted.

The effective management and treatment of sludge [57] in wastewater treatment entail several key processes aimed at facilitating its disposal or reuse [58,59]:

1. Thickening: Before undergoing digestion, sludge is commonly thickened to decrease [60] its water content and optimize the utilization of digester capacity. This thickening process serves to prevent dilution of feed material, thereby reducing energy requirements for heating and maintaining pH stability within the digester. Various methods, such as gravity thickeners or dissolved air flotation thickeners, are utilized for this purpose, ensuring that the sludge is concentrated adequately for effective digestion without impeding pumping and mixing processes;
2. Stabilization: Anaerobic digestion stands as a prevalent method for stabilizing sludge, transforming it from a malodorous and readily decomposable state into a mostly odorless and stable material suitable for disposal. During this process, acid-forming bacteria decompose organic matter into organic acids, which subsequently undergo conversion into methane and carbon dioxide. Despite requiring substantial investment and skilled operators, effectively managed anaerobic digestion can yield biogas suitable for power generation;
3. Dewatering: Dewatering plays a critical role in reducing the volume of sludge for disposal. Various methods, including filter or belt presses and drying beds, are employed to extract water from the sludge. In the filter or belt presses, flocculants are introduced to aid in dewatering, while drying beds rely on sand filters to drain water from the sludge during the drying process. Ensuring proper maintenance of equipment like belt presses is essential to prevent problems such as sludge buildup.

In summary, efficient sludge handling ensures the effective treatment and disposal of sludge produced during WWT processes. This contributes significantly to environmental sustainability and resource recovery endeavors.

3.6. Biogas Production

Biogas, a gas fuel formed through the breakdown of organic matter, mainly comprises a mixture of methane and carbon dioxide [61]. It is produced from sewage, manure, waste, or agricultural crops [62]. Energy is a crucial aspect of WWT, so it is important to focus on generating "green energy" and reducing power consumption by utilizing biogas. While biogas primarily contains methane, carbon dioxide, and moisture, it can also contain small amounts of impurities such as hydrogen sulphide, halogenated compounds, siloxanes, ammonia, and solid particles. To effectively use biogas for heat and electricity generation, these impurities must be removed. In the past, biogas has mainly been used for heating boilers and powering incinerators [12]. However, as electricity costs rise, as well as the imperative to reduce carbon emissions, and concerns regarding the reliability and quality of electricity supply to treatment facilities, it has become a viable business model for plants with a capacity exceeding 25 million liters per day using anaerobic sludge digestion. A well-operated 'Biogas to Energy' facility has the potential to meet between 50% and 60% of the electricity needs for Wastewater Treatment Works (WWTWs) and fulfil most of the heat requirements for mesophilic sludge digestion [63].

3.7. The Most Common Process

The activated sludge process stands out as the most employed technique for biologically removing nitrogen from both municipal and industrial wastewater. Given its importance and the widespread presence of operational facilities, significant research has focused on refining operational tactics and improving the layout of individual plants [64].

Below (Figure 3) is a standard flowchart illustrating the typical components found in an activated sludge WWTP [15,65,66].

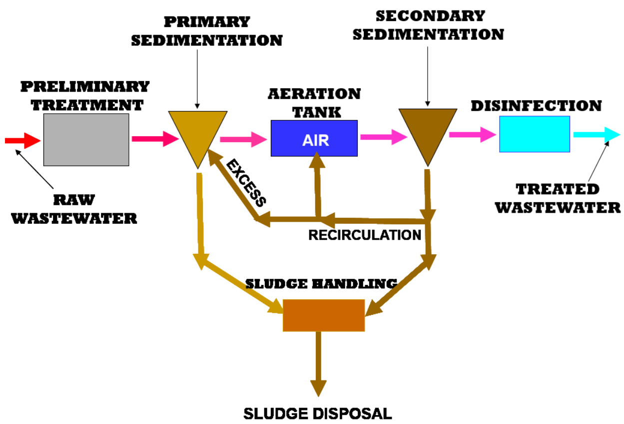

Figure 3. Activated sludge process (modified from Bengtson [65]).

The preliminary treatment phase initiates with screening, flow measurement, and possibly grit removal. Subsequently, the primary clarifier segregates settleable suspended matter, directing underflow to sludge treatment and disposal while directing overflow to an aeration tank. Within the aeration tank, aerobic microorganisms catalyze the biological oxidation of organic matter, supported by dissolved oxygen. Aeration sustains dissolved oxygen levels and ensures thorough mixing. The activated sludge, housing microorganisms, settles in the secondary clarifier and is reintroduced into the aeration tank to maintain microbial concentration, thereby optimizing WWT efficiency [65]. Post-secondary clarification, disinfection procedures are executed before the final discharge, employing methods such as chlorination, ozonation, UV radiation, or maturation ponds [20].

4. Energy Consumption

The overall energy consumption during the treatment phase depends on several factors, both inherent and external. These factors include the volume of wastewater generated, the nature and concentration of pollutants present, the level of treatment provided (primary, secondary, or tertiary), and the targeted quality standards for the treated water [67]. Additionally, factors such as the type of treatment facility (centralized or decentralized), the scale of the system, the type of sewage collection system (separate or combined), the need for pumping, and local climatic conditions indirectly influence energy requirements [68]. Energy is also utilized for conditioning or stabilizing the sludge produced by WWTPs through processes like anaerobic digestion, composting, or incineration [69].

Moreover, further treatment and transportation of wastewater effluent are conducted based on its intended use. Energy consumption during the primary treatment phase remains relatively stable. However, the energy demand in the secondary treatment stage varies significantly depending on the type and capacity of the WWTP. Treatment methods such as the activated sludge process (ASP) with extended aeration, sequential nitrification and denitrification, sequencing batch reactor (SBR), and oxidation ditch typically require higher energy inputs [70]. In a conventional ASP, aeration of the biological tank alone represents nearly 60% of the total energy consumption of the treatment plant, with additional energy expended on sludge pumping, processing, and disposal [71].

Conversely, treatment methods like trickling filters, lagoons, constructed wetlands, and adsorption-biology systems are comparatively more energy-efficient. However, energy consumption tends to increase in advanced treatment processes used for nutrient removal and sludge conditioning. The energy demand for advanced biological treatment with nutrient removal and filtration is approximately 50% higher than that of conventional WWTPs [13]. Figure 4 illustrates typical average energy consumption values for various treatment units.

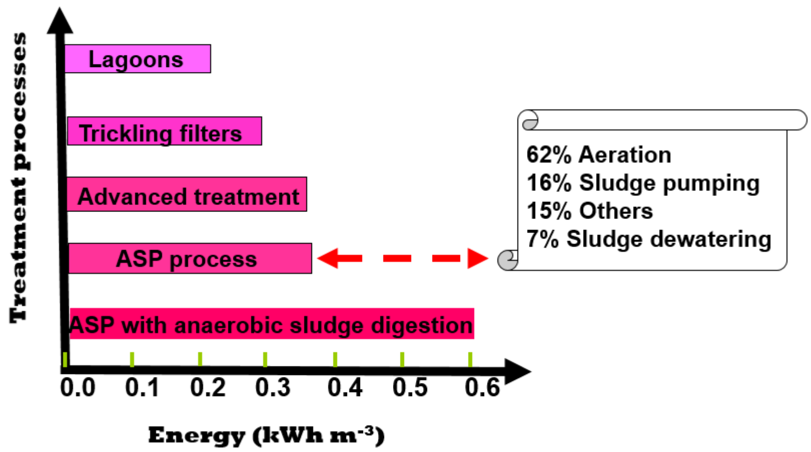

Figure 4. Average energy consumption for various treatment units (modified from Gude [70]).

The primary energy sources used include electricity, natural gas, and other fossil fuels. Worldwide, the average energy consumption for wastewater treatment varies: USA—0.52 kWh m^{-3}, China—0.31 kWh m^{-3}, Japan—0.304 kWh m^{-3}, Korea—0.243 kWh m^{-3}, and Europe—0.42 to 0.53 kWh m^{-3} [72]. This high energy consumption results in significant GHG emissions, including carbon dioxide, methane, and nitrous oxide (N_2O). The carbon footprint, a measure of its impact on climate change, is heavily influenced by WWTPs, accounting for nearly 70% of the carbon footprint of the urban water cycle. Among these, approximately 56% of emissions are attributed solely to energy usage [69]. Small WWTPs often face significant fluctuations in influent load and unstable treatment conditions. These challenges are exacerbated by potential shortages of skilled personnel, driven by economic constraints. Consequently, these factors can lead to reduced energy efficiency, as measured by energy consumption per unit of treated wastewater. Moreover, the type of WWTP, whether centralized or decentralized, influences the energy demand of the system [73]. Thus, the selection of decentralized systems should be made with careful consideration of the specific circumstances, especially where local water reuse is feasible. Additionally, changes in climatic variables such as temperature, precipitation, and snowfall, attributed to climate change, are expected to impact overall energy usage soon [74]. Projections indicate that climate-related stresses over the next century will amplify seasonal variations in flow rates and result in more frequent operational challenges.

5. Overview

This section offers an overview of studies and research conducted on various aspects related to energy optimization in WWT processes. These studies cover a wide range of topics, including optimizing energy use during the aeration process, proposed methods for reducing energy consumption during sludge treatment, and adjustments to pump operations. Additionally, attention is given to incorporating new equipment and maximizing the use of existing infrastructure, as well as the integration of renewable energy sources in WWT. Furthermore, this section explores modeling individual processes within WWTPs, simulating energy consumption predictions, and conducting comparative evaluations among different WWTPs. The inclusion of theoretical thermodynamic studies and case studies provides comprehensive insights into energy optimization strategies throughout different stages of WWT.

5.1. Energy Optimization during Aeration Process

Table 4 lists the aim and results of each study focused on reducing energy consumption in the aeration process. Following this, each study is described in detail. A critical review then highlights the significant findings and opportunities of these studies, as summarized in Table 5.

Table 4. Summary of studies aiming to reduce energy consumption in the aeration process.

Year	Aim	Results	Reference
2007	Optimization challenges in the alternating activated sludge process.	Achieve a 10% reduction in pollution load.	[75]
2017	A data-driven approach for modeling and optimizing the aeration process in a large-scale WWTP in the Midwest.	Achieve a 31.4% decrease in energy consumption for aeration through oxygen reduction, while maintaining the effluent water quality in accordance with the standard requirements.	[76]
2020	Employing a hybrid modeling approach to streamline weather-dependent operations and optimize energy consumption at Italy's largest WWTP.	Aeration energy consumption could be reduced from 4.1% to 6.8%.	[77]
2015	A model was implemented in 10 WWTPs in Greece to assess their carbon footprint. Based on these findings, energy-saving strategies were proposed to reduce both energy consumption and greenhouse gas (GHG) emissions.	At the Psyttalia WWTP, implementing different DO scenarios results in a reduction ranging from 6% to 10.1%. For substantial energy savings of around 11.2%, an approach that considers both DO values and sludge age can be employed, potentially leading to energy savings of approximately 4500 MWh per year.	[78]
n.d *	An extensive optimization experiment was conducted to refine DO control in the aerobic tanks at the Käppala WWTP in Stockholm, Sweden.	The overall outcome resulted in a notable 18% decrease in total airflow, while maintaining treatment efficiency.	[7]

Table 4. *Cont.*

Year	Aim	Results	Reference
2017	The Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne, an operator in the Paris metropolitan area, has implemented initiatives to optimize energy consumption.	By reducing the injected air flows, starting at 8 $Nm^3 h^{-1}$ and gradually decreasing to 6.5, and then 4 $Nm^3 h^{-1}$, the estimated energy consumption reduction in 2013 was approximately 0.7 MWh per ton of removed nitrogen. This estimation is based on an energy consumption rate of 0.033 kWh Nm^{-3} of produced air.	[79]
2019	Investigate strategies to improve energy efficiency at a WWTP in Malaysia focusing on the aeration tank. Assess the energy savings from implementing High-Speed Turbo compressors compared to roots blowers.	Achieving a reduction in energy consumption by up to 42% would result in a return on capital expenditure which would be achieved within 1.22 years.	[80]
2005	Develop and implement a fuzzy logic controller to regulate aeration at the Taradell WWTP. The goal is to conserve energy while maintaining effluent quality by integrating data from DO and oxidation-reduction potential signals from the fuzzy controller.	The implementation results in energy savings of over 10%, ensuring that effluent quality is not compromised.	[81]

* n.d.: no date.

Table 5. Strengths and opportunities of the studies mentioned in energy optimization during aeration process.

Reference	Strengths	Potential Advancements
[75]	Incorporating genetic algorithm.	Investigation into the effects of frequent aeration switching, including its impact on aerator lifespan.
[76]	Implementing a data-mining algorithm for optimizing the aeration process.	Development of models with increased frequency of data collection.
[77]	Optimizing energy usage based on weather conditions.	Broader exploration of factors beyond weather.
[78]	An evaluation of energy consumption and carbon footprint across 10 WWTPs in Greece, accompanied by recommendations for efficiency improvements and savings.	Assessment of energy consumption and carbon footprint across multiple WWTPs in Greece, considering their applicability to other plants.
[7]	Implementation of individual control in aeration zones.	Adoption of individual control in aeration zones, with a more comprehensive analysis of associated costs.
[79]	Creation and execution of targeted energy-saving techniques designed to decrease total energy usage.	Development and application of targeted energy-saving techniques to reduce overall energy usage, with a focus on evaluating their long-term performance.
[80]	Deploying of High-Speed Turbo compressors.	Implementation of High-Speed Turbo compressors, recognizing potential limitations to their applicability based on plant scale and operational conditions.
[81]	Development and applying a fuzzy logic controller for aeration regulation.	Design and execution of a fuzzy logic controller for aeration regulation, with consideration of challenges related to data accuracy and algorithm complexity.

Holenda et al. [75] focused on optimizing the alternating activated sludge process, tackling its inherent complexities resistant to conventional optimization methods. Utilizing a stochastic optimization approach, specifically a genetic algorithm, it aimed to pinpoint the most efficient aeration strategy (timing of air-on and air-off cycles) to minimize pollution in effluent discharge. Additional operational considerations, like aeration energy usage and excess sludge management, were considered. The outcomes showcased the effectiveness of the genetic algorithm in efficiently discovering optimal solutions, resulting in a notable 10% reduction in pollution discharge. Notably, there was also a decrease in aeration energy consumption, though the potential impact of frequent turbine switching during brief aeration periods was not addressed. To validate these results, further investigations are recommended at both pilot-scale and full-scale treatment facilities.

A data-driven approach was utilized to model and enhance the aeration process at a large-scale WWTP in the Midwest. The primary aim was to reduce energy usage while maintaining water quality standards. By employing data-mining algorithms, models were developed to establish a clear relationship between input and output variables from the WWTP. The findings indicate significant energy savings while ensuring water quality remains within acceptable bounds. Two optimization models were devised, each with specific control limits, accounting for both energy efficiency and water quality improvement. In optimization models, the objective is to reduce effluent concentrations of contaminants (such as carbonaceous biochemical oxygen demand (CBOD), total suspended solids (TSS), total suspended particles (TSP), and total dissolved particles (TDP)) to improve water quality, while simultaneously minimizing average dissolved oxygen (DO) levels to decrease process energy consumption. These optimization models are formulated with constraints to maintain acceptable water quality standards, ensure blower capacity requirements are met, and guarantee sufficient oxygen levels for mixing. In an energy-focused scenario, there was a notable 31.4% reduction in aeration oxygen consumption while maintaining effluent water quality at levels equal to or better than standard requirements. However, some variability was observed in the optimized results due to the lack of high-frequency data for parameters such as CBOD and TSS. To improve the control system, it is essential to increase the frequency of sampling for these influent variables [76].

An additional research endeavor introduces a hybrid modeling approach aimed at enhancing weather-based operation and optimizing energy usage for the largest WWTP in Italy. The challenge addressed in this research involves determining the underlying structure of clustered data when only observed values are available. To evaluate the quality of clustering, two quantitative indices, the Bayesian Information Criterion (BIC) and the Silhouette coefficient using Euclidean distance, along with two general criteria, were employed. The dataset comprises volumetric influent flow rate (Qin), concentrations of ammonium ($N\text{-}NH_4$), chemical oxygen demand (COD), and TSS obtained through daily composite sampling from the plant's influent spanning from 2009 to 2016. Additionally, two environmental factors, Precipitation (PI) and Temperature (T), were gathered from the Piedmont Environmental Protection Agency. Moreover, for each scenario, two critical parameters influencing biological activities and aeration energy consumption—wastewater temperature and air temperature at the blower inlet in the aeration units—were adjusted based on empirically derived relations with air temperature. Consequently, seven weather-based influent scenarios were integrated into the process simulation model, alongside the proposal of various aeration strategies. The results of the process simulation model confirmed that aeration energy consumption could be decreased from 4.1% to 6.8% across the seven influent scenarios [77].

A study conducted in Greece aimed to assess the energy consumption and carbon footprint of WWTPs. A model was utilized to evaluate the carbon footprint, and strategies to reduce energy-saving, energy consumption, and GHG emissions were proposed. Operational data from 10 WWTPs in Greece, with capacities ranging from 15,000 to 4,000,000 population equivalents, revealed an average annual specific energy consumption of approximately 38 kWh per population equivalent (PE), varying from 15 to 86 kWh per PE. The annual average GHG emissions for Greek WWTPs were around 94 kCO_2e per PE, ranging from 61 to 161 kg CO_2e per PE. Extended aeration systems exhibited the highest CO_2 emissions, while conventional activated sludge systems had the lowest. Key strategies for mitigating GHG emissions in the wastewater industry were identified, and a case study demonstrated potential strategies for energy savings and GHG emission reduction. The study suggests that reducing DO set points and sludge retention time could significantly save energy and decrease GHG emissions. For the WWTP of Psyttalia, applying various DO scenarios resulted in a reduction of 6 to 10.1%. To achieve significant energy savings (of the order of 11.2%), a combined approach involving DO value and sludge age can be adopted, resulting in energy savings of approximately 4500 MWh per year [78].

To enhance the energy efficiency of the Käppala WWTP in Stockholm, Sweden, a comprehensive optimization experiment was conducted by Thunberg et al. [7], to refine the DO control in the aerobic tanks. In the tested strategy, individual control was applied to each aerated zone, reshaping the spatial dissolved oxygen profile to prevent unnecessarily high levels. Through the implementation of ammonium- and DO-feedback controllers, the strategy demonstrated increased responsiveness to variations in influent load. The overall outcome was a notable 18% reduction in total airflow while maintaining treatment efficiency.

Since around 2000, the Syndicat Interdépartemental pour l' Assainissement de l' Agglomération Parisienne, an operator in the Paris metropolitan area, has implemented initiatives aimed at optimizing energy consumption. These efforts are designed to reduce both costs and associated environmental impacts. By utilizing energy meters for sector-specific data collection, consumption has been analyzed at different scales (macroscopic, plant, process). Electric power has emerged as the primary energy source in WWTPs, with biological treatment processes, particularly the aeration process, being the primary consumers. Building on this understanding, for optimization, energy use has been outlined, requiring intervention at three levels. Initially, the optimizing of operating costs should cover the entire treatment chain, including all associated costs (such as reagents), to make informed operational decisions. Then, considerations at the process and equipment levels are essential to determine appropriate courses of action. Based on the above, aeration reduction was applied to the nitrification process at the Seine-Grésillon (SEG) WWTP, serving as a model for a method-based approach. The regulatory parameter considered at SEG was the minimum air velocity, which started at 8 Nm h^{-1} and gradually decreased to 6.5, and then 4 Nm h^{-1}. Despite a significant reduction in the injected air flows, there was no adverse impact on effluent quality upon the completion of nitrification. In 2013, the total volume of injected air was 40% lower than that in the same period in 2012. Using an energy consumption rate of 0.033 kWh Nm^{-3} of produced air, the estimated energy consumption reduction in 2013 was approximately 0.7 MWh per ton of removed nitrogen [79].

Aziz et al. [80] investigated strategies to improve energy efficiency at a WWTP in Malaysia with a daily average flow capacity of 67,500 m^3. Their focus was on reducing energy consumption in the biological tank, particularly the aeration tank. Through the implementation of High-Speed Turbo compressors, energy consumption could potentially decrease by up to 42% compared to using roots blowers. Calculations suggest that the expected return on capital expenditure would be achieved within 1.22 years, indicating that the proposed system not only enhances cost efficiency but also generates revenue within a short time frame. Fiter et al. [81] detailed the development and implementation of a fuzzy logic controller to regulate aeration at the Taradell WWTP, designed for an average inflow of approximately 2000 m^3 d^{-1}. The primary goal of this control system is to conserve energy while maintaining effluent quality. The fuzzy controller integrates data from DO and oxidation-reduction potential signals. Simulation results show that fuzzy logic effectively controls aeration, leading to energy savings of over 10% while maintaining high removal levels.

Advanced optimization techniques like stochastic optimization and data-driven modeling have led to significant improvements in WWTPs' efficiency, with reductions in pollution discharge and energy consumption. Optimization models now balance energy efficiency with water quality improvement, emphasizing sustainability. Despite promising outcomes, challenges remain for further research, including the need for better data collection, comprehensive risk analysis, validation across diverse contexts, and detailed economic evaluations.

Addressing these challenges will enhance the reliability and applicability of optimization efforts, advancing the efficiency and sustainability of WWTPs.

5.2. Proposed Methods to Reduction in Energy during Sludge Treatment

Table 6 presents the aims and outcomes of several studies concentrating on minimizing energy usage in sludge treatment procedures. Subsequently, in Table 7, each study is expounded upon, accompanied by a thorough critique that underscores the notable discoveries and potential advancements gleaned from these studies.

Table 6. Compilation of research targeting energy reduction in sludge treatment.

Year	Aim	Results	Reference
2012	Reduction in energy consumption of Autothermal Thermophilic Aerobic Digestion (ATAD).	Achieved a 22% decrease in single-stage ATAD and an 18% reduction in two-stage ATAD.	[4]
2023	Development of a simulation-based methodology for energy saving in a sludge incineration unit, utilizing data from the WWTP in Gdynia, Poland.	Resulting in a 6% reduction in overall energy consumption for the incineration unit.	[82]
2008	Solid waste management through plasma gasification at the Psyttalia WWTP, Athens, Greece.	Demonstrated energy self-sufficiency and generated 2.85 MW of electrical energy.	[8]
2015	Study conducted on five WWTPs in Catalonia.	Highlighted anaerobic digestion as a promising technology for extracting energy from wastewater, emphasizing the need for implementing strategies to optimize biogas production.	[83]
2016	Examination of energy production, usage, and conservation at Ringsend WWTP in Ireland, including improved biosolids management.	Achieving savings up to 75% in electrical energy consumption.	[10]

Table 7. Strengths and opportunities of the studies mentioned in proposed methods for reducing energy consumption during sludge treatment.

Reference	Strengths	Potential Advancements
[4]	Focus on optimizing energy usage in ATAD processes.	Further research needed on responses to unusual sludge compositions.
[82]	Creation of methodologies for energy savings in sludge incineration.	Further research needed on the applicability and transferability to other WWTPs.
[8]	Comprehensive strategy integrating sludge treatment and electricity generation.	Further research needed on the analysis of economic aspects and scalability.
[83]	Highlights the importance of biogas utilization.	Further research needed on the increase in biogas production.
[10]	Significant electricity savings and a forward-thinking goal of achieving energy neutrality, providing a model for other plants.	The feasibility of improved biosolids management and other technical strategies may depend on existing infrastructure and technology readiness, necessitating further exploration. Additionally, a detailed cost–benefit analysis is proposed, along with addressing the practical challenges and costs associated with large-scale implementation.

Rojas and Zhelev [4] introduced a dynamic autothermal thermophilic aerobic digestion (ATAD) to minimize the energy consumption. Through a global sensitivity analysis, key operating conditions affecting energy requirements are identified, highlighting the most promising optimization variables: aeration flow rate, reaction time, and sludge flow rate. The optimization problem, recognizing the discontinuous nature of ATAD, is formulated using a sequential approach for dynamic optimization. The problem is implemented in MATLAB® fmincon function and solved using the eSS algorithm for two case studies, one with a single-stage and the other with a two-stage digestion. Optimizing the single-stage system results in a 22% reduction in energy consumption, while the two-stage system achieves an 18% improvement. Despite its proven benefits in other domains, optimization remains relatively uncommon in wastewater engineering.

In a groundbreaking approach, the energy-saving status potential of a sewage sludge incineration unit within a WWT system was systematically simulated using data collected from the WWTP in Gdynia, Poland. In the system under analysis, there are several components including a rotary dryer, fluidized bed furnace (FBF), condenser, bag filter, scrubber, mixer, and three heat exchangers (HEXs). The energy performance of the system, which includes variables such as temperature in Fluidized Bed (TFB), Steam Heat Transfer Rate (SHTR), and Dryer Residence Time (DRT) in the sewage sludge, was forecasted based on changing parameters. This process involved training and testing data from the ASPEN PLUS software V11.4 and the use of a sophisticated in-house code (robust chained multi-output regression) to validate optimizer predictions. In conclusion, the methodology developed in this study demonstrates a 6% reduction in the overall energy consumption with values of TFB, SHTR, and DRT at 890.13 °C, 249.79 kW, and 9.70 h, respectively, for the incineration unit of a sewage sludge disposal plant [82].

Plasma gasification presents an appealing and environmentally friendly solution for managing solid wastes while harnessing energy. This research demonstrates the potential for energy utilization in treating sewage sludge through a comprehensive process that integrates plasma gasification, pre-drying, and electric energy generation. The application of this approach, examined through a case study involving sludge from the Psyttalia WWTP, reveals that the proposed method is not only energy self-sufficient but also results in a net production of 2.85 MW of electrical energy [8].

Silvestre et al. [83] examined five WWTPs in Catalonia and found that, depending on plant configuration and operation, between 39% and 76% of the total electric energy consumed in the WWT process could be supplied by the biogas produced. Using the elemental composition proves effective in estimating the energy content of various WWTP streams and conducting an energy flow analysis for the entire facility. The energy flow analysis shows that 67% of the initial energy content of raw wastewater is transferred to sewage sludge, and the anaerobic digestion process recovers 52%, converting it into biogas. These results highlight anaerobic digestion as a promising technology for energy recovery from wastewater. They also indicate the necessity for strategies to improve biogas energy production.

Awe et al. [10] investigated energy production, usage, and conservation at a WWTP in Ireland with the goals of (i) identifying energy and resource recovery strategies, (ii) exploring their potential applications within the plant, and (iii) advocating for widespread, large-scale implementation across WWTPs. Various strategic options have been evaluated and proposed to enhance the energy efficiency of the Ringsend WWTP and achieve energy neutrality, serving as a model for other treatment plants in Ireland. The adoption of technical strategies, such as improved biosolids management, could result in electricity savings of up to 75% at the Ringsend WWTP.

The studies above provide diverse perspectives on enhancing energy efficiency and sustainability in WWT. Rojas et al. [4] introduced a dynamic ATAD approach, achieving notable energy savings through optimization techniques. While effective, the study highlights the underutilization of optimization in wastewater engineering. Adibimanesh et al. [82] focused on sewage sludge incineration, revealing insights into energy reduction potentials, albeit with potential limitations in scalability. Mountouris et al. [8] explored plasma gasification, demonstrating energy self-sufficiency but with possible constraints on generalizability. Silvestre et al. [83] emphasized biogas production, underscoring the importance of anaerobic digestion while identifying areas for improvement. These studies collectively advance our understanding of energy optimization in WWT, yet challenges such as scalability and applicability persist, necessitating further research for widespread implementation.

5.3. Emphasizing Multiple Stages of WWT

The goals and the results of studies aimed at reducing energy consumption across various treatment stages are outlined in Table 8. Each study is then elaborated upon, followed by a critical assessment that highlights both the significant findings and potential advancements (Table 9).

Table 8. Compilation of research targeting minimizing energy usage across various treatment processes.

Year	Aim	Results	Reference
2018	Introduction of a statistical analysis method for unit energy consumption in conventional Finnish WWTPs.	Potential maximum energy savings could reach as high as 1.26 kWh kg^{-1} COD.	[84]
2012	Conducting an energy audit covering influent pumping, the aeration process, UV disinfection, and solids handling at Crested Butte WWTP of Colorado.	Presents best practices for facility managers to readily adopt and achieve energy efficiency.	[85]
2012	Optimization of a WWT process, focusing on carbon and nitrogen removal.	Utilizes model-based analysis to enhance energy efficiency in WWT.	[86]
2011	Integration of turbo blowers as a replacement for conventional blowers in WWTPs.	Demonstrative trials were conducted at two WWTPs, Franklin in New Hampshire and the Central Advanced in Fort Myers, Florida. Estimated to result in an 32% and 17% reduction in energy consumption, respectively, demonstrating the significant potential for energy savings with this technology.	[87]

Table 9. Strengths and potential benefits of the research mentioned regarding the emphasis on multiple stages within WWTP.

Reference	Strengths	Potential Advancements
[84]	Analysis of energy consumption in Finnish WWTPs provides valuable insights into current energy usage patterns and potential areas for optimization	Careful consideration required for practical implementation of proposed technologies could lead to improved energy efficiency and reduced operational costs.
[85]	A detailed analysis conducted in Crested Butte, Colorado, focusing on energy conservation strategies offers a thorough examination of specific measures to reduce energy consumption in WWT.	Consideration should be given to the potential challenges associated with adapting the findings to various environmental contexts.
[86]	In-depth examination of carbon and nitrogen removal processes.	Addressing limited consideration of economic and thermal factors in carbon and nitrogen removal processes could enhance the feasibility and cost-effectiveness of WWT methods.
[87]	The study confirms the potential for significant energy savings with the adoption of turbo blowers in WWTPs, highlighting a promising technological solution for energy efficiency.	Detailed cost–benefit analyses, including initial investment costs and long-term maintenance considerations, could inform decision-making processes and maximize the potential benefits of adopting turbo blowers in WWTPs.

A statistical analysis method was conducted to assess unit energy consumption in conventional Finnish WWTPs, with a focus on the Mikkeli WWTP as a case study. The average energy consumption across Finnish WWTPs was determined to be 0.49 kWh m^{-3}. This study identifies significant energy-saving opportunities in secondary treatment, screening and grit removal, and influent pump stations. An innovative retrofitting strategy is proposed, integrating four emerging energy-neutral or positive technologies to optimize the utilization of chemical energy content in wastewater. These technologies include enhanced primary sedimentation, staged anaerobic fluidized membrane bioreactor (SAF-MBR) with completely autotrophic nitrogen removal over nitrite process (CANON), and co-digestion of sludge with organic food waste. The potential maximum energy savings could reach as high as 1.26 kWh kg^{-1} COD, providing a viable solution to bridge the energy deficit at Mikkeli WWTP and achieve a net positive energy surplus of 1.15 kWh kg^{-1} COD [84].

Daw et al. [85] emphasized the significance of energy usage in wastewater facilities by conducting a case study at Crested Butte, Colorado's WWTP. The study involved a process energy audit, revealing substantial opportunities for energy conservation. These opportunities primarily focus on power-intensive unit processes like influent pumping, aeration, ultraviolet disinfection, and solids handling. Through this case study, the authors introduced best practices that facility managers can readily implement to achieve both energy and financial savings in water and WWT operations. Depending on the proposed energy-saving strategies in the processes—influent pumping, aeration, ultraviolet disinfection, and solids handling—energy reductions ranging from 10% to 35%, 10% to 90%, 50%, and 100%, respectively, are achieved. Some of the extended strategies include pump replacement, deactivation of mixers when blowers are operating, replacement of dissolved oxygen meters, modification of the UV disinfection unit, and retrofitting piping to feed sludge directly from the thickened sludge tank to the centrifuge.

Descoins et al. [86] conducted a study focusing on optimizing a WWT process, specifically targeting carbon and nitrogen removal. The process involves activated sludge reactors coupled with an anaerobic digestion reactor, where nitrification and de-nitrification biochemical reactions occur due to the biological activity of microorganisms. The study utilizes sets of equations to determine optimal steady-state configurations, with a primary emphasis on electrical efficiency. While the focus is on electrical efficiency, the study suggests that other potential areas of investigation, such as economic costs or thermal criteria, could also be integrated into the objective functions. Through analysis, two limiting factors to overall energy efficiency are identified: ammonium production in the digestion process and the availability of C substrate for denitrification in the activated sludge reactors. The study suggests that model-based analysis holds promise for enhancing energy efficiency in WWT. It enables the optimization of process variables, facilitates the comparison of technologies, and allows for a rigorous consideration of energy aspects in computations.

Bell and Abel [87] advocated for the integration of turbo blowers as a substitute for conventional blowers in WWTPs to diminish power usage and operating costs. Turbo blowers present several benefits, including the elimination of oil, liquid, or belts for maintenance, resulting in substantial savings in both operations and upkeep. Demonstrative trials took place at two WWTPs: the Franklin WWTP in New Hampshire and the Central Advanced WWTP in Fort Myers, Florida. The Franklin WWTP, established in the 1970s with a design average capacity of 30.2 cubic meters per minute, showcased a projected 32% decline in power consumption upon implementing turbo blowers in the aeration process. In Fort Myers, housing two advanced wastewater treatment plants (AWWTPs), the Central and South AWWTPs, designed for annual average capacities of approximately 50,000 and 55,000 cubic meters, respectively, turbo blowers were tested for the sludge holding tank. The installation of turbo blowers at both WWTPs is estimated to result in an approximate 17% reduction in energy consumption, affirming the significant potential for energy savings offered by this technology.

The studies by Gurung et al. [84], Daw et al. [85], and Descoins et al. [86] each provide valuable insights into optimizing energy consumption in WWT, albeit with different emphases and methodologies. Gurung et al. [84] conducted a statistical analysis across Finnish WWTPs, identifying energy-saving opportunities and proposing innovative retrofitting strategies. Their approach offers promising solutions to bridge energy deficits and achieve net positive energy surplus. However, the study's focus on specific technologies may need clarification regarding its applicability to other WWT facilities. Daw et al. [85] conducted a process energy audit at Crested Butte, Colorado's WWTP, highlighting substantial opportunities for energy conservation. Their case study introduces practical strategies for achieving energy and financial savings in water and WWT operations. While the proposed energy-saving strategies are effective, the study's applicability may be constrained by its single-case focus. Descoins et al. [86] focused on optimizing a WWT process, specifically targeting carbon and nitrogen removal. Their study utilizes mathematical models to determine optimal configurations, emphasizing electrical efficiency. While the model-based analysis holds promise for enhancing energy efficiency, the study's narrow focus on electrical efficiency may overlook other important factors such as economic costs and thermal criteria. Overall, these studies contribute valuable insights into energy optimization in WWT, offering practical strategies and highlighting the importance of considering various factors in achieving energy efficiency. However, challenges such as limited applicability and narrow focus on specific technologies or objectives may be grounds for wider application in WWT practices.

Bell and Abel [87] demonstrate the significant energy savings that can be achieved through the adoption of turbo blowers in WWTPs. This finding highlights the potential of turbo blowers as a promising technological solution for improving energy efficiency in WWT processes. A detailed cost–benefit analysis, which would take into consideration not only the initial capital investment cost but also the long-term maintenance implications of the turbo blowers, would present an intriguing perspective. Such an analysis would provide valuable insights for decision makers and help to maximize the potential benefits of implementing turbo blowers in WWTPs.

5.4. Modification in the Operation of the Pumps

Table 10 presents studies that concentrate on adjusting pump operation to minimize energy usage. Following this, Table 11 offers a critical appraisal of these studies.

Table 10. Studies focused on pump operation optimization.

Year	Aim	Results	Reference
2011, 2012	Development of a framework for modeling variable-speed pumps in the preliminary WWT process.	Utilizing data-driven approaches for pump modeling.	[1,88]
2017	Creation of an innovative data-driven methodology aimed at holistically assessing pump systems.	Differentiating between long-term and short-term phenomena. Developing a user-friendly performance index. Early detection of potential issues. Extracting valuable insights from data. Suggesting economically feasible solutions.	[89]

Table 11. Strengths and opportunities of the studies mentioned on modification in the operation of the pumps.

Authors	Strengths	Potential Advancements
[1,88]	Development and application of data-mining algorithm to model pump operations.	Investigation into potential limitations under various operating conditions.
[89]	Development of innovative data- driven methodologies for evaluating pump systems.	Further validation and implementation in diverse operating environments.

A framework has been devised and established to simulate variable-speed pumps within the context of preliminary wastewater treatment processes [1,88]. The performance of these pumps is characterized by two crucial parameters: energy consumption and water flow rate. The models outlined in this study were developed using data-mining algorithms. Data were gathered from a sizable municipal wastewater processing facility and underwent preprocessing to generate usable datasets. Two types of models have been created: one based on 5 min data and the other constructed using 30 min data. The accuracy of these models has been validated. The models presented in this study offer significant advantages for the management of wastewater processing plants. Models derived from 5 min data enable dynamic optimization of pump performance, while those developed from 30 min data are suitable for pump scheduling purposes. The research successfully accomplished its goal of modeling pumps based on data.

Enhancing energy efficiency in WWTPs presents a significant challenge, particularly within pump systems, where conserving energy can offer substantial economic and environmental benefits. Despite the presence of online sensors, current practices often lack comprehensive data for accurate pump system performance. An innovative data-driven methodology has been developed to thoroughly evaluate pump systems, thereby assisting plant managers in achieving energy savings. This approach can address both long-term and short-term fluctuations, generating a user-friendly performance index, identifying potential issues at an early stage, extracting valuable insights from the database, and proposing economically feasible solutions based on available information, such as energy costs and inflow. Moreover, this methodology is highly adaptable and can be effectively applied even in domains with limited information beyond energy costs and inflow [89].

The studies conducted by Zhang and Kusiak [1], Zhang et al. [88], and Torregrossa et al. [89] present innovative methodologies for enhancing energy efficiency in WWT, with a particular focus on pump systems. Zhang and Kusiak [1] and Zhang et al. [89] developed frameworks for simulating variable-speed pumps, creating models for dynamic optimization and scheduling purposes. These models, built using data-mining algorithms and validated for accuracy, provide significant benefits for managing WWTPs. However, despite their promising solutions, the models depend heavily on the availability of comprehensive data, which may pose challenges for implementation, especially in facilities that lack sufficient data infrastructure.

Torregrossa et al. [89] introduced a data-driven methodology for thoroughly evaluating pump systems, aimed at assisting plant managers in achieving energy savings. This approach addresses both long-term and short-term fluctuations, generating user-friendly performance indices and proposing economically feasible solutions. Moreover, its adaptability makes it applicable even in domains with limited information. However, the study's effectiveness may be constrained by its reliance on available data and the complexity of implementing proposed solutions in real-world settings. While these studies contribute valuable insights and methodologies for enhancing energy efficiency in WWT, challenges related to data availability and implementation complexity need to be addressed for broader adoption and impact in practice.

5.5. Addition of Equipment and Utilization of Existing Infrastructure

Table 12 provides brief descriptions of studies proposing the addition of equipment or the utilization of existing infrastructure in wastewater treatment facilities. Following this, each study is described in detail. Finally, Table 13 presents a critical review of these studies.

Table 12. Concise description of studies suggesting the addition of equipment or the utilization of existing infrastructure.

Year	Aim	Results	Reference
2015	Conduct a comprehensive energy benchmarking analysis on two full-scale WWTPs utilizing oxidation ditches as the primary treatment process to determine an optimal solution for site optimization.	Reduction of 55% in BOD reaching the oxidation ditch. Reduction of 75% in TSS reaching the oxidation ditch. Reduction of 12% in NH_4 reaching the oxidation ditch. Aeration requirements reduced by 49% kWh d^{-1} Significant decrease in greenhouse gas emissions: from 1510 kg of CO_2 equivalent per day to 415 kg of CO_2 equivalent per day.	[90]

Table 12. *Cont.*

Year	Aim	Results	Reference
2019	Examine the design and categorization of aeration systems, with a focus on critical parameters and factors that impact the aeration process, including oxygen transfer efficiency, diffuser fouling, strategies for mitigating fouling, and the selection of appropriate diffusers.	Fine-bubble diffuser systems are identified as highly efficient in Polish WWTPs. Maintaining the condition and efficiency of these systems is crucial. Concerns raised regarding the energy intensity of the aeration process.	[91]
2016	Assess the potential for energy reduction through the implementation of variable-speed drives and energy-efficient motors at Alexandria East WWTP.	Integration of variable-speed drives resulted in an average annual energy savings of 15,804.5 kWh. Implementation of energy-efficient motors led to an average annual energy savings of 2628 kWh.	[92]
2017	Investigate the selection and optimization of turbine designs in four WWTPs in Ireland.	Optimized system efficiencies at different sites range from 73% to 76%. Turbine costs vary from EUR 315 to 1708 per kW depending on the type. Utilizing pump-as-turbines results in system efficiencies of 58–62%. Incorporating two pump-as-turbines in parallel further improves efficiency by an additional 5%.	[2]
2020	Repurpose existing WWTP tank infrastructure to partially store wastewater during the day and schedule purification processes for nighttime in a Romanian WWTP with an anaerobic-anoxic-oxic process configuration.	Operational costs reduced by 47%. Effluent quality improved by 25%. Aeration energy reduced by 36.7%. Increase in total pumping energy. Overall operational energy decreased due to the significant reduction in aeration energy.	[93]
2020	Improve primary sludge separation through hydrocycloning at a WWTP in Jaipur, India, which utilizes the biological-activated sludge process.	Installation of VFDs resulted in 17.15% improvement in power factor; 17.48% increase in energy efficiency. Implementation of VFDs and PLC-based PID Controllers for DO set-point in the bioreactor led to a 65.74% reduction in aeration energy consumption. Integration of hydrocyclones with smart aeration control achieved a 71.46% decrease in aeration energy requirements.	[94]

Table 13. Strengths and potential benefits of research on equipment addition and infrastructure utilization in WWTPs.

Reference	Strengths	Potential Advancements
[90]	Comparison of energy consumption between two different plants with recommendations for optimization.	Further research needed to assess the economic viability of proposed solutions.
[91]	Approach aimed at controlling proper aeration and reducing energy consumption in a WWTP in Poland.	Explore the application of controls to other facilities for broader impact.
[92]	Application of technological solutions to reduce energy consumption across large-scale operations.	Future studies should include comprehensive monitoring to evaluate the efficiency of implemented measures.
[2]	Creation of optimal technological solutions tailored to increase energy efficiency within 4 WWTPs in Ireland.	Validate and certify proposed methodology through further research in diverse operational settings.
[93]	Strategy to leverage current plant infrastructure to reduce operating costs and enhance effluent quality.	Investigate the impact of the strategy in different settings through additional research and evaluation.

Table 13. *Cont.*

Reference	Strengths	Potential Advancements
[94]	Aim to enhance primary sludge separation through hydrocycloning, potentially improving overall treatment efficiency.	Future research should replicate experimental investigations across multiple WWTPs to generalize results.

Belloir et al. [90] conducted an extensive total energy benchmarking analysis at two full-scale WWTPs employing oxidation ditches as the primary treatment process. Both sites had similar influent pollutant concentrations and effluent discharges. Site 1 and Site 2 were found to have total energy consumption rates of 2.32 kWh m^{-3} and 0.98 kWh m^{-3}, respectively, encompassing electrical, manual, chemical, and mechanical consumptions. Despite Site 2 demonstrating lower energy consumption, the benchmarking exercise highlighted significant limitations, including insufficient aeration capacity in the oxidation ditches and potential non-compliance with effluent regulations. Mass and energy balances were employed to determine the optimal solution for site optimization, which recommended the construction of primary settling tanks at Site 2. The installation and operation of a primary settling tank are expected to result in a 55% reduction in BOD, a 75% reduction in TSS, and a 12% reduction in NH_4 reaching the oxidation ditch, effectively addressing compliance issues. Additionally, the aeration needs (kWh d^{-1}) are projected to decrease by 49%, leading to a substantial reduction in greenhouse gas emissions, from 1510 kg of CO_2 equivalent per day to 415 kg of CO_2 equivalent per day.

Drewnowski et al. [91] delved into the construction and classification of aeration systems, shedding light on key parameters and factors influencing the aeration process. These include oxygen transfer efficiency, diffuser fouling, methods for addressing fouling, and diffuser selection. The overview also touches on "smart control" systems in WWT and the impact of implementing a control strategy based on the Supervisory Control and Data Acquisition (SCADA) system. This implementation leads to decreased energy consumption for aeration in activated sludge bioreactors. The primary focus of the study is to compare aeration control strategies for energy process control and to develop an effective control system. Data gathered from this research contribute to optimizing biological nutrient removal and oxygen consumption, utilizing sensors like DO and nitrate/ammonium (NO_3/NH_4), and implementing control systems in the aeration zone of the bioreactor at the "Dębogórze" WWTP. While the prevalence of highly efficient fine-bubble diffuser systems in Polish WWTPs is advantageous, maintaining their condition and efficiency remains crucial. The study also raises concerns about the energy intensity of the process, suggesting the need for more advanced control strategies despite the prevalent use of simpler automatic control methods.

Ghoneim et al. [92] focused on the four most energy-intensive processes of a WWTP: waste-activated sludge, primary clarification, solids dewatering, and heating. These introduce alternative energy management strategies aimed at reducing overall energy consumption and mitigating energy peaks in large-scale WWTPs. The Alexandria East WWTP (with average daily flow of 800,000 m^3 d^{-1}) serves as a case study to assess the potential for energy reduction through the implementation of Variable-Speed Drives (VSDs) and Energy-Efficient Motors (EEMs). Following the implementation of a VSD, the average annual energy savings amount to 15,804.5 kWh. Similarly, after the adoption of EEMs, the average annual energy savings stand at 2628 kWh.

Power et al. [2] conducted a study on the selection and optimization of turbine designs in four WWTPs in Ireland. The study investigates the influence of flow rate variations during storm events and changes in water demands on the optimal turbine design. Additionally, the selection of turbines is examined, emphasizing the ideal design in terms of power output and cost. The research explores low-cost options for settings with low head by employing multiple pump-as-turbines in parallel. The results reveal significant disparities between power output estimates based on average flow rates and turbine efficiency compared to those derived from detailed design optimization, with underestimates of up to 12%. The optimized system efficiencies across the sites range from 73% to 76%, and turbine costs vary from EUR 315 to 1708 kW^{-1} depending on the type. The use of pump-as-turbines yields system efficiencies of 58–62% and employing two pump-as-turbines in parallel further enhances the efficiency of these low-cost systems by an additional 5%.

Simon-Várhelyi et al. [93] proposed a strategy to optimize the utilization of existing infrastructure in the WWTP by employing tanks for partial storage of wastewater received during the day, with treatment scheduled for nighttime. The operational approach aims to shift a portion of the WWTP's electrical energy consumption from peak daytime hours to nighttime when energy costs are typically lower. This contributes to improving the overall balance of the electrical power generation system. The case study focuses on a Romanian WWTP utilizing an anaerobic-anoxic-oxic process configuration. In the most favorable scenario, considering the overall performance of the WWTP, operational costs are reduced by 47%, and effluent quality is enhanced by 25%. This is achieved by storing a portion of the influent wastewater from 2:00 p.m. in available tanks during the day, with the initiation of WWT scheduled for 12:00 a.m. at night. Additionally, there is a 36.7% reduction in aeration energy usage. While there is an increase in total pumping energy, the overall operational energy decreases, primarily due to the reduction in aeration energy consumption.

Khatri et al. [94] introduced a control configuration utilizing smart embedded controls for WWTPs, with a specific focus on improving on primary sludge separation through hydrocycloning. The study was conducted at a WWTP in Jaipur, India, which utilizes the biological-activated sludge process and has a capacity of 125 m^3 per day. The experimental investigations yielded the following key findings: 1. The installation of VFDs resulted in a 17.15% improvement in power factor, a 17.48% increase in energy efficiency, and enhanced operational stability, including protection against overload current. 2. Implementing VFDs and PLC-based PID controllers for DO set-point control in the bioreactor achieved a remarkable 65.74% reduction in aeration energy consumption. 3. Integrating hydrocyclones with smart aeration control led to a substantial 71.46% decrease in aeration energy requirements compared to open-loop systems. 4. The WWTP demonstrated its capability to operate at an enhanced treatment capacity through the combined implementation of DO control, hydrocycloning, and minor retrofitting in tertiary treatment processes.

The studies by Belloir et al. [90], Drewnowski et al. [91], Ghoneim et al. [92], Power et al. [2], and Simon-Várhelyi et al. [93] offer valuable insights into energy optimization strategies within WWTPs, each focusing on distinct aspects and processes. Belloir et al. [90] conducted a comprehensive total energy benchmarking analysis at two full-scale WWTPs, identifying energy-saving opportunities and proposing solutions for optimization. The study's strengths lie in its detailed assessment of energy consumption and its recommendations for improving operational efficiency. However, limitations such as potential non-compliance with effluent regulations highlight challenges in achieving sustainable energy practices.

Drewnowski et al. [91] investigated the construction and classification of aeration systems, highlighting the significance of efficient control strategies for energy savings. Their study contributes to optimizing biological nutrient removal and reducing oxygen consumption. However, concerns persist regarding energy intensity and the necessity for more advanced control methods.

Ghoneim et al. [92] concentrated on diminishing energy consumption in four energy-intensive processes of WWTPs, introducing alternative energy management strategies. Their research offers practical insights into implementing variable-speed drives and energy-efficient motors for energy reduction. However, the broader applicability across different WWTPs may vary.

Power et al. [2] delved into turbine design optimization in WWTPs, emphasizing the impact of flow rate variations and changes in water demand. Their study provides valuable findings regarding the selection and optimization of turbines. Nonetheless, disparities in power output estimates and costs underscore challenges in achieving optimal efficiency.

Simon-Várhelyi et al. [93] introduced a strategy to optimize existing infrastructure in WWTPs by transitioning wastewater treatment to nighttime, with the goal of reducing operational costs and energy consumption during peak hours. Although their approach demonstrates potential for enhancing overall energy balance and effluent quality, challenges such as increased pumping energy necessitate further consideration. In summary, these studies offer diverse methodologies and insights into energy optimization in WWTPs. However, challenges such as regulatory compliance, implementation complexity, and variability in outcomes underscore the importance of comprehensive and tailored approaches to achieve sustainable energy practices in WWT.

5.6. Application of Renewable Energy Sources

In Table 14, references to studies advocating for the implementation of Renewable Energy Sources (RES) are provided, along with brief descriptions. Subsequently, Table 15 offers a more detailed critical review of these studies.

Table 14. Studies proposing the application of RES.

Year	Aim	Results	Reference
2017	Investigating the energy consumption of the WWTP in Rzeszów.	The energy generated from biogas meets 74.3% of the electrical and 95.5% of the heat requirements compared to the total energy consumption.	[6]
2017	Introducing an optimal design approach to maximize the sustainability of an integrated WWTP equipped with a Combined Heat and Power (CHP) unit.	Optimization results demonstrate a 16.9% reduction in total cost rates and a 5.3% decrease in environmental impacts. The power generated by the optimized system can fulfill 47% of the WWTP's power demand while meeting the entire heat requirement.	[95]
2021	Exploring scenarios of high penetration of renewable energy sources in WWTPs using dynamic simulation and optimization.	Highly renewable wastewater systems provide flexibility services to power and heating networks, along with benefits such as heat production and improved effluent quality suitable for various applications.	[5]
2020	Presenting an approach to design solar Photovoltaic (PV) systems to minimize energy consumption in aeration processes.	This approach assists the industry in making decisions regarding PV investments, supporting wastewater utilities in embracing sustainable management practices. Consequently, it advances the integration of renewable energy sources within the wastewater sector.	[3]
2021	Recommending a series of energy efficiency measures including CHP, PV systems, and hydroelectric power.	Achieved a total energy savings of 71%.	[96]
2015	Investigating key strategies to optimize the energy balance in two advanced municipal WWTPs (Wolfgangsee-Ischl and Strass WWTPs) with nutrient removal.	Implementation of additional strategies, such as incorporating organic waste into digesters through co-digestion, harnessing thermal energy from wastewater for space heating, and exploring innovative processes for wastewater and waste management, holds the promise of transforming municipal wastewater systems into "energy-positive" entities.	[9]
2013	Optimizing biogas production at Prague's Central WWTP through various strategies.	Increased biogas production to 12.5 m^3 per population equivalent per year resulted in a rise in specific energy production from approximately 15 to 23.5 KWh per population equivalent per year.	[97]

Table 15. Strengths and potential benefits of research on the application of renewable energy sources.

Reference	Strengths	Potential Advancements
[6]	Achieving high levels of energy self-sufficiency through anaerobic digestion technology.	Research on optimizing performance under diverse operating conditions.
[95]	Creation of optimized designs ensuring the highest sustainability for WWTPs.	Further development and testing to refine and validate the proposed designs.
[5]	Considering high rates of renewable energy for designing self-sufficient systems.	Exploring strategies to overcome implementation barriers for broader adoption.
[3]	Introducing an innovative methodology for designing solar photovoltaic systems for WWTPs.	Conducting extensive field trials to validate and enhance the methodology for practical use.
[96]	Proposing a flexible energy-saving system with high potential for savings.	Expanding financial analyses to include diverse regional markets and conditions.
[9]	Implementing combined measures for energy self-sufficiency.	Investigating the long-term environmental and social impacts of combined measures.
[97]	Integrating strategies to improve biogas production.	Developing comprehensive models to assess constraints and optimize cost-efficiency.

A study conducted by Masłoń [6] delves into the energy consumption of the WWTP in Rzeszów. The findings reveal that the total energy consumption of the Rzeszow WWTP in 2016 was approximately 0.865 kWh m^{-3} and 48.2 kWh per population equivalent per year. The average electrical and thermal energy consumption indicators were 0.468 and 0.397 kWh m^{-3}, respectively. Electric energy consumption was notably lower than comparable values at other facilities and in other countries. This outcome could be attributed to the highly advanced treatment technologies utilized and the stringent water quality standards in WWTP in Rzeszów. The anaerobic digestion technology with a CHP system employed at the Rzeszów WWTP significantly contributes to energy self-sufficiency. Biogas energy enables covering 74.3% of electrical and 95.5% of heat needs relative to the overall energy consumption of the WWTP. The average relation between total energy generation and consumption at Rzeszów WWTP was 83.6%. Throughout the research period, the total energy recovery indicator stood at 0.52 kWh m^{-3}. The average electric energy and heat energy recovery indicators were recorded at 0.3 and 0.31 kWh m^{-3}, respectively. Identifying the energy balance of the WWTP was the initial but crucial step in developing an improved biogas utilization scheme.

Lee et al. [95] presents an optimal design approach aimed at maximizing the sustainability of an integrated WWTP featuring inclusion of a CHP unit. A comprehensive analysis, employing thermo-environ-economic methods, is conducted to assess the impacts of component efficiencies, temperature variations in heat exchangers, and the pressure ratio of the compressor and gas turbine. The optimization results show a 16.9% reduction in total cost rates and a 5.3% decrease in environmental impacts. The power generated by the optimized system is capable of meeting 47% of the power demand for the WWTP, with also fulfilling the entire heat requirement of the system. The feasibility of achieving high levels of renewable energy integration (up to 100%) in WWTPs was investigated using dynamic simulation and optimization techniques. The key findings are summarized as follows: (1) The highest renewable energy-integrated wastewater system resulted in a net present cost that was 20–65% higher than the reference value. This increase was primarily influenced by the availability of solar energy resources. (2) It is recommended to design renewable energy and storage systems with a self-sufficiency ratio of 70% to achieve optimal cost-effectiveness across scenarios. (3) The levelized cost of treated water for large-capacity WWTPs showed no significant increase in high renewable energy penetration (above 90%) compared to the reference case (grid-supplied electricity). The analysis primarily focused on installation and operation costs. However, high renewable energy-integrated wastewater systems offer additional benefits, such as providing flexibility services to power and heating networks, as well as co-benefits such as heat production and improved effluent quality for various applications.

Campana et al. [5] and Colacicco and Zacchei [3] introduced the integration of solar photovoltaic (PV) technology into WWTPs with the aim of reducing energy consumption in aeration processes. A novel methodology is introduced to design solar PV systems specifically tailored for this purpose. New analytical equations and parameters are presented, considering factors such as air temperatures, solar irradiation, biological kinetics, dissolved oxygen levels, and mechanical oxygenation. These are used to determine the peak power of PV systems that maximize the self-consumption of aeration blowers installed in the oxidation tanks of WWTPs. This method allows for a direct preliminary design and a calibrated estimation of energy power. To validate this approach, three main aspects are discussed: (i) oxidation tanks contribute up to 30% of the energy consumption in a WWTP; (ii) wastewater temperature varies throughout the year, particularly in smaller WWTPs; (iii) DO levels decrease with an increase in wastewater temperature. This methodology is intended to assist the industry in making informed decisions regarding PV investments, thereby aiding wastewater utilities in adopting sustainable management practices. Ultimately, it contributes to the advancement of renewable integration within the wastewater sector.

A series of energy efficiency measures recommended by Qandil et al. [96] have the potential to achieve an 11% reduction in total annual energy consumption. Additionally, by harnessing untapped waste hydropower energy at WWTPs, two primary technologies are proposed, offering an additional 15% energy savings through year-round operation, and generating an annual production of 131,400 kWh. Moreover, the biogas generated at WWTPs can be utilized to power a 42 kW biogas turbine unit for combined heat and power generation, resulting in a projected yearly electricity output of 366,534 kWh and an additional 42% energy savings. The combined effect of these measures, along with the installation of a 200 kW DC photovoltaic system, leads to a comprehensive 71% reduction in energy consumption. Economic analyses, based on US market costs and a 15.7-year payback period without incentives, were conducted to assess the feasibility of implementing these proposed systems.

The key strategies to optimize the energy balance in municipal wastewater systems were explored by Nowak et al. [9]. In Austria, two advanced municipal WWTPs (Wolfgangsee-Ischl and Strass WWTPs) with nutrient removal achieve energy self-sufficiency. These plants exhibit a total electric energy consumption lower than the energy produced through (CHP) generation utilizing biogas from anaerobic sludge digestion. Additional measures, such as introducing organic waste to digesters (co-digestion), utilizing thermal energy from wastewater for space heating, and exploring alternative wastewater and waste management options through innovative processes, have the potential to make municipal wastewater systems "energy-positive".

An effort to optimize biogas production at Prague's Central WWTP through various strategies was conducted by Jenicek et al. [97], which included enhanced primary sludge separation, thickened waste activated sludge, lysate centrifuge implementation, increased operational temperature, and improved digester mixing. These optimizations resulted in a significant increase in biogas production to 12.5 m^3 per population equivalent per year. Consequently, there was a notable rise in specific energy production from approximately 15 to 23.5 kWh per population equivalent per year. A comparison with energy self-sufficient WWTPs with exceptionally low energy consumption suggests that, with proper anaerobic digestion technology optimization, even WWTPs with 'standard' energy consumption can achieve or come close to achieving energy self-sufficiency.

Masłoń's study [6] provides a detailed analysis of the energy consumption of a specific WWTP. It highlights the effectiveness of anaerobic digestion technology combined with a CHP system in achieving energy self-sufficiency. However, since the study focuses on a single facility, its findings may not be generalizable to other WWTPs.

Lee et al. [95] present an optimal design approach aimed at maximizing the sustainability of an integrated WWTP, demonstrating significant reductions in total cost rates and environmental impacts. While the study offers promising results, further exploration is needed to determine the applicability of the optimization approach to various WWTP configurations and contexts.

Campana et al. [5] and Colacicco and Zacchei [3] focus on integrating solar PV technology into WWTPs to reduce energy consumption in aeration processes. Their methodologies offer practical tools for designing solar PV systems tailored for WWTPs. However, further research is needed to assess the feasibility and scalability of these systems across various WWTP sizes and locations.

Qandil et al. [96] propose energy efficiency measures and renewable energy technologies for WWTPs, demonstrating substantial reductions in energy consumption. Nonetheless, the economic feasibility and implementation challenges of these measures in different regions need to be thoroughly assessed.

Nowak et al. [9] and Jenicek et al. [97] explore strategies for achieving energy self-sufficiency in WWTPs through various measures, including co-digestion, thermal energy utilization, and biogas production optimization. These studies highlight the potential for WWTPs to become energy-positive. However, further research is needed to investigate the scalability and applicability of these strategies in diverse WWTP settings.

Overall, these studies offer diverse methodologies and insights into energy optimization in WWTPs. To enable broader implementation in WWT practices, future research would do well to focus on issues such as feasibility, scalability, and economic viability.

5.7. Modeling Individual Processes in WWTPs

In Table 16, the papers detailing and proposing the modeling of individual processes in WWTPs are summarized, while in Table 17, these papers are critically reviewed.

Table 16. Studies proposing modeling of individual processes in WWTPs.

Year	Aim	Results	Reference
2019, 2020	Flow modeling, simulation techniques, measurement of air transfer efficiency, and redesigning the aeration facility at the San Pedro del Pinatar WWTP.	Energy consumption reduction exceeding 20%.	[98,99]

Table 17. Strengths and potential benefits of the research in modeling individual processes in WWTPs.

Reference	Strengths	Potential Advancements
[98,99]	Presentation of a strategy aimed at enhancing the operation of the aeration equipment, leading to decreased energy consumption.	Further verification of the effectiveness of the measures under various operating conditions.

The examination of the tools used to identify and correct deviations from optimal operating points in the aeration equipment of San Pedro del Pinatar (Murcia, Spain) was tested by Avilés et al. [98,99]. It addresses inherent deficiencies in the installation to better meet the oxygen requirements of microorganisms and improve the efficiency of gas-to-liquid phase transfer. The objectives include minimizing aeration needs, reducing pressure losses, optimizing air supply pressures to prevent excessive energy consumption for the same airflow, and refining the control strategy for actual working conditions. Key techniques such as flow modeling, simulation, measuring air transfer efficiency, and redesigning the aeration facility at the San Pedro del Pinatar WWTP were crucial in achieving significant consumption reductions exceeding 20%.

Avilés et al. [98,99] conducted studies aimed at optimizing the aeration equipment at the San Pedro del Pinatar WWTP in Spain. The research focused on addressing deficiencies in the installation to improve oxygen transfer efficiency and reduce energy consumption.

Utilizing various tools such as flow modeling, simulation, and efficiency measurements, the studies identified and corrected deviations from optimal operating points. Consequently, significant reductions in energy consumption exceeding 20% were achieved through the redesign of the aeration facility and optimization of air supply pressures. Overall, the studies offer valuable insights into enhancing the efficiency of aeration systems in WWTPs. However, further investigation into the applicability of the proposed solutions to other facilities and the scalability of these solutions may be warranted, thus suggesting avenues for future research.

5.8. Simulation for Predicting Energy Consumption

In Table 18, studies proposing simulation as a method for predicting energy consumption in WWTPs with the aim of energy saving are referenced. Table 19 delineates a critical review of these studies.

Table 18. Studies advocating simulation as a method to forecast energy usage in WWTPs with the goal of energy conservation.

Year	Aim	Results	Reference
2016	Develop an energy optimization strategy focused on green energy.	Proposed a methodology that engineers can use to predict energy consumption throughout the WWTP lifecycle.	[100]
2019	Introduce a simulation-based approach to establish a comprehensive link between treatment processes and energy demand/production.	Identified potential energy savings of up to 5000 MWh annually, along with improved effluent quality.	[101]
2019	Apply fuzzy clustering to investigate the relationship between energy consumption and its influencing factors. Evaluate the performance of RBF model vs. multi-variable linear regression.	Results provide a crucial theoretical foundation for energy conservation efforts in WWTPs.	[102]
2019	Analyze operational simulation results for four cases to identify energy-efficient operational methods and opportunities to optimize power consumption at a Japanese WWTP.	Demonstrated potential for 10% reduction in energy consumption.	[103]
2014	Demonstrate how activated sludge modeling and computational fluid dynamics (CFD) can be used to optimize energy consumption in WWTPs.	Achieved energy savings ranging from 1.3% to 3.3%.	[104]

A strategy for optimization energy usage in WWTP is introduced, involving a thorough analysis from a green energy perspective. This approach is illustrated through a case study of a WWTP in a rural town. The methodology is tailored for use by design engineers to predict energy consumption over the entire lifecycle of the WWTP. It can be further developed into user-friendly software, which would be valuable for WWTP management to evaluate annual operational expenses. The proposal incorporates the utilization of both linear and logistic growth models to forecast how infrastructure usage will evolve with population growth. The logistic growth model is preferred as it more accurately reflects infrastructure utilization over its lifecycle, including the delay between infrastructure completion and reaching maximum capacity. Optimizing energy efficiency in industrial plants is most effective when on-site renewable energy sources are integrated into the analysis alongside opportunities for technological enhancements. Identifying these opportunities entails a thorough examination of plant operations across various scenarios [100].

Borzooei et al. [101] presented a comprehensive and integrated strategy aimed at enhancing the energy efficiency of Castiglione Torinese, which is the largest WWTP in Italy, boasting a capacity of over 2,000,000 equivalent inhabitants. This study focuses on wastewater and sludge treatment units to identify potential measures for improving energy efficiency. The authors introduce a multi-step simulation-based methodology to establish a thorough connection between treatment processes and energy demand and production.

Additionally, they propose a scenario-based optimization approach to determine the most effective performance for the WWTP. The findings underscore the potential for significant energy savings, up to 5000 MWh annually, along with improvements in effluent quality through operational adjustments alone.

Table 19. Strengths and opportunities of studies utilizing simulation for predicting energy consumption.

Reference	Strengths	Potential Advancements
[100]	Innovative approach that considers different scenarios and uses both linear and logistic growth models to estimate energy consumption.	Applying and validating the methodology in WWTPs of varying scales to ensure its practical applicability.
[101]	Comprehensive approach to optimizing energy consumption at Italy's largest WWTP.	Opportunity to further assess the methodology's effectiveness and apply it to additional WWTP sites.
[102]	Use of fuzzy clustering and neural networks for forecasting energy consumption.	Discussing and demonstrating the real-world application and validation of the proposed approach.
[103]	Demonstrated potential for a 10% reduction in power consumption by adopting energy-efficient operational methods, highlighting the feasibility of sustainable practices in WWTPs.	Evaluating the generalizability of the findings to other WWTPs with different configurations or operational conditions.
[104]	Demonstrated the potential of activated sludge modeling and CFD to optimize energy consumption.	Validating the actual implementation and feasibility of these approaches, while accounting for site-specific factors and resource constraints, to further optimize the energy-saving potential.

Li et al. [102] utilized the fuzzy clustering method to categorize sample data from various WWTPs, exploring the relationship between energy consumption and influencing factors across different categories. The study identified variations in energy efficiency among these categories and underscored that the same influencing factors demonstrate different intensities across various types. Subsequently, a neural network was employed to predict energy consumption, utilizing both the complete dataset and category-specific data for model training and testing. The results revealed that the Radial Basis Function (RBF) model [105], leveraging data from the subset, outperformed the multivariable linear regression model. Overall, the findings of this study lay down a fundamental theoretical groundwork for energy conservation in WWTPs.

A study conducted by Kato et al. [103] focused on a WWTP in Japan, which has been operational since 1980. This facility utilizes a conventional activated treatment process and has a capacity of 189,040 m^3 d^{-1}. The study aimed to analyze power consumption and reported operational simulation results for four different cases. The findings revealed that adopting an energy-efficient operational method could potentially reduce power consumption by 10%. Although the best result among the four cases was identified, the study suggests that there might still be room for further optimization. Key findings from the research include the following: 1. Excessive rotational speed control led to an increase in power consumption per unit discharge rate. 2. Analyzing power consumption and implementing operational improvements based on daily report data proved to be effective. 3. VFDs were found to be ineffective for pumps in WWTPs due to differing operational point patterns compared to water supply pumps. 4. Operating pumps to maintain a consistently high wastewater level in the pump well did not effectively save energy. Therefore, the study suggests the need for further examination of additional cases to achieve optimal conditions. Additionally, the potential use of artificial intelligence (AI) in determining optimum operational conditions is highlighted as a promising avenue for future research.

Gussem et al. [104] provide a case study demonstrating how activated sludge modeling and CFD can optimize the energy consumption of a WWTP that already employs advanced control based on online nutrient measurements. Currently, the aeration basins at the Antwerp-South WWTP operate sequentially, with variable flow direction and points of inflow and outflow over time. Activated sludge modeling reveals that transitioning from the existing alternating flow-based control to simultaneous parallel feeding of all aeration tanks could result in a 1.3% energy savings. CFD calculations confirm that water velocity remains sufficient even if some impellers in the aeration basins are shut down. Simulation results from the activated sludge model suggest that coupling aeration control with impeller control and automatically deactivating some impellers during inactive aeration periods could lead to energy savings of 2.2 to 3.3% without compromising nutrient removal efficiency.

The study by Badea et al. [100] introduces a strategy for energy optimization in WWTPs, with a focus on green energy perspective and a lifecycle approach. The proposed methodology, which is designed for use by design engineers, holds promise for the development of user-friendly software tools to support WWTP management. The effectiveness and applicability of the approach in diverse WWTP settings constitute an area for future investigation.

The research by Borzooei et al. [101] focuses on enhancing the energy efficiency of a large WWTP in Italy through simulation-based methodologies and scenario-based optimization. The study highlights the potential for significant energy savings, along with improvements in effluent quality, through the implementation of operational adjustments.

Li et al. [102] utilized fuzzy clustering and neural network methods to categorize and predict energy consumption in WWTPs based on influencing factors. Their study lays a strong theoretical groundwork for energy conservation in WWTPs, showcasing the potential of advanced modeling techniques. In summary, the studies presented offer valuable contributions to the field of energy optimization in WWTPs. However, further research is needed to assess the scalability, applicability, and practical implementation of the proposed methodologies in diverse WWT settings. By addressing these areas, the findings can be strengthened and the adoption of energy-efficient practices in the industry can be facilitated.

Kato et al. [103] showcased the potential for a 10% reduction in power consumption through the implementation of energy-efficient operational methods. This underscores the practicality and effectiveness of sustainable practices in WWTPs. To bolster these findings, it may be beneficial to evaluate the possibility of generalizing these results to other WWTPs with different configurations or operational conditions.

Gussem et al. [104] successfully demonstrated the potential offered by the use of activated sludge modeling and CFD for optimizing energy consumption in WWTPs. It might be useful to validate the practical application and feasibility of these approaches. This includes considering specific factors and resource constraints for fully optimizing energy-saving opportunities.

5.9. Comparative Evaluation between Various WWTPs

Tables 20 and 21 refer to studies that conducted comparative evaluations between different WWTPs, providing a critical review of them, respectively.

Table 20. Comparative evaluation studies.

Year	Aim	Results	Reference
2019	A comprehensive analysis of the current operational status of WWTPs in China.	The study examines potential avenues for improvement to overcome the barriers, providing valuable insights for optimizing municipal wastewater management in China for enhanced efficiency and sustainability.	[106]
2020	The utility of energy consumption benchmark values as a robust management tool for assessing the optimal energy efficiency of 243 WWTPs across Greece.	Utilizes the current situation of Greek WWTPs and incorporates the most effective techniques to suggest optimized measures aimed at improving their operational efficiency.	[107]
2020	Examining the energy demands of 17 WWTPs in Greece that utilize the activated sludge method, serving populations ranging from 1100 to 56,000 inhabitants.	The study uncovered significant variations in energy requirements per flow rate or per inhabitant among the surveyed WWTPs, suggesting opportunities for improvements to reduce overall energy consumption.	[108]

Table 21. Strengths and opportunities of the studies mentioned in comparative evaluation between various WWTPs.

Reference	Strengths	Potential Advancements
[106]	An analysis of challenges faced by WWTPs in China and potential directions for improvement.	Development and proposal of specific technical solutions to address the identified challenges in Chinese WWTPs.
[107]	An examination of statistical data on energy consumption in WWTPs in Greece.	Inadequate discussion on the application of best practices.
[108]	A comprehensive analysis of energy requirements in 17 WWTPs in Greece, utilizing the activated sludge method.	Practical implementation of specific optimization proposals to reduce energy consumption in the studied WWTPs.

Lu et al. [106] conducted a comprehensive analysis of the current operational status of WWTPs in China. The research identified key barriers to enhancing the operational efficiency of these plants, considering factors such as plant scale, geographical distribution, variations between cities and counties, and the impact of environmental policies and additional facilities. The study revealed that an underdeveloped sewer network significantly contributed to low operating ratios (utilization degree of designed treatment capacity), especially in north China. Specific plant situations indicated that 19% of plants are still operating under overload conditions. Other challenges include high energy consumption (0.313 kWh m^{-3}) and delayed implementation of sludge disposal (up to 40% improperly disposed), primarily due to inadequate sewer and sludge management. The study concludes by discussing potential directions for improvement to overcome these barriers, offering valuable insights for optimizing municipal wastewater management in China towards greater efficiency and sustainability.

Another study examined the utility of energy consumption benchmark values as a robust management tool for assessing the optimal energy efficiency of WWTPs. It emphasized the role of benchmarking in identifying opportunities for energy savings and prioritizing optimization measures. By comparing the performance of sewage treatment plants with benchmark values, the study highlighted the potential for energy optimization and cost reduction. Operational and technical data were collected from 243 licensed WWTPs across Greece. The statistical analysis of energy data revealed that secondary processing contributes the most to energy consumption, accounting for 72%. Other contributors include pre-treatment (13%), treatment sludge (8%), tertiary treatment (6%), and primary treatment (1%). The study discusses the use of benchmark energy indicators, noting that the kWh m^{-3} indicator may not fully represent WWTP energy consumption, especially in combined or mixed systems affected by rainwater dilution. Instead, indicators like kWh per people equivalent per year and kWh kg^{-1} COD removed are suggested as more representative for energy benchmarking purposes [107].

Similar research investigated the energy demands of 17 activated sludge WWTPs in Greece, serving populations ranging from 1100 to 56,000 inhabitants (population equivalent). These plants exhibited average daily incoming flow rates from 300 to 27,300 m^3 d^{-1}. The daily wastewater production per inhabitant ranged from 0.052 m^3 per population equivalent per day to 0.426 m^3 per population equivalent per day, with an average volume of 0.217 $\pm$ 0.114 m^3 per population equivalent per day. The study revealed significant variation in energy requirements per flow rate or per inhabitant among the surveyed WWTPs, suggesting potential for improvements to reduce overall energy consumption [108].

All studies provide valuable insights into the operational efficiency and energy consumption patterns of WWTPs in different regions, offering potential directions for improvement.

In their comprehensive analysis, Lu et al. [106] examined WWTPs in China and identified significant obstacles to operational efficiency, such as underdeveloped sewer networks, high energy consumption, and poor sludge management. The study underscores the critical challenges faced by Chinese WWTPs, emphasizing the necessity for enhanced infrastructure and management strategies to boost efficiency and sustainability.

Similarly, the study examining energy consumption benchmark values in Greek WWTPs [107,108] provides valuable insights into energy consumption patterns and potential optimization areas. By analyzing operational and technical data from a significant number of WWTPs, the study establishes benchmarks for assessing energy efficiency. It also highlights limitations in using traditional energy indicators like kWh m^{-3} and suggests alternative indicators for more accurate benchmarking. Further research is needed to address the identified barriers and implement effective strategies for improving operational efficiency and sustainability in wastewater management systems.

5.10. Theoretical Thermodynamic Study

In Table 22, the main research points proposing the application of thermodynamic studies aimed at energy self-sufficiency are presented, followed by a critical review of these points (Table 23).

Table 22. Theoretical thermodynamic study.

Year	Aim	Results	Reference
2021	A theoretical thermodynamic study investigating the energy self-sufficiency of a WWTP.	The findings indicate that the proposed system can meet up to 109% of the WWTP's energy requirements.	[109]

Table 23. Critical review of theoretical thermodynamic study.

Authors	Strengths	Potential Advancements
[109]	Theoretical thermodynamic study on achieving energy self-sufficiency in WWTPs.	Further practical applications.

Erguvan and MacPhee [109] present a theoretical thermodynamic study that examines the energy self-sufficiency of a WWTP. The system comprises four major subsystems: an activated sludge process, an anaerobic digester, Brayton and Rankine cycles. A secondary compressor, integrated into the Brayton cycle, powers aeration in the activated sludge system to improve overall system efficiency. The study investigates energy and exergy efficiencies, varying parameters in both the WWTP and power cycles. Factors such as BOD, DO level, turbine inlet temperature, compression ratio, and preheater temperature are analyzed for their impact on self-sufficiency. This study presents several key findings: 1. The energy efficiency of the overall system ranged from 35.7% to 46.0%, while exergy efficiency varied from 30.6% to 33.55%. 2. Optimal efficiencies were achieved at specific parameters: turbine inlet temperature (1200 °C), air preheater temperature (427 °C), compression ratio (10), and effluent biological oxygen demand (20 mg L^{-1}) and dissolved oxygen level (2 mg L^{-1}). 3. The self-sufficiency ratio ranged from 76.6% to 109.4%, indicating the potential for a self-sufficient system using the proposed multigeneration setup. 4. Optimal parameter selection led to significant increases in the self-sufficiency ratio, up to 42% compared to the least efficient system and 12.7% compared to the case study. 5. Changes in effluent BOD minimally affected efficiency but had a substantial impact on oxygen requirements. Small increases in desired DO levels significantly raised oxygen demand. 6. The system proved to be self-sufficient when the DO level was below 3 mg L^{-1}, with the self-sufficiency ratio ranging from 85% to 107% based on varying DO levels. 7. Integrating a Rankine cycle into the Brayton cycle for lower compression ratios could boost power production by up to 52.9%. 8. Turbine inlet temperature and DO level were identified as the most influential parameters on self-sufficiency ratio variations, while desired effluent BOD and air preheater temperature had lesser effects. 9. Turbine inlet temperature was found to be the most crucial factor affecting self-sufficiency ratio, followed by DO concentration, due to their significant impact on aeration power requirements.

Erguvan and MacPhee's theoretical thermodynamic study [109] offers valuable insights into achieving energy self-sufficiency in WWTPs through a multigeneration setup. By analyzing the energy and exergy efficiencies of various subsystems, such as activated sludge processes and power cycles, the study identifies optimal parameters for maximizing self-sufficiency. Key findings include the significant potential for enhancing the self-sufficiency ratio through optimal parameter selection, the limited impact of effluent BOD on efficiency but notable influence on oxygen requirements, and the critical role of turbine inlet temperature and dissolved oxygen level in self-sufficiency variations. The study's comprehensive analysis provides a clear understanding of the factors influencing energy self-sufficiency in WWTPs and offers practical recommendations for improving efficiency.

By conducting experimental validation and feasibility assessment, this research aims to bridge the gap between theoretical understanding and practical implementation of energy self-sufficiency in WWTPs. The insights gained from this study will inform future strategies for sustainable WWT and energy management, contributing to the transition towards more efficient and environmentally friendly WWT practices.

5.11. Other Case Studies

In this concluding subsection of the research evaluation, the authors provide references and critically review other comprehensive works conducted within the last decade. Table 24 presents a summary of the referenced studies, while Table 25 offers a critical review of their methodologies and findings.

Table 24. A summary of the main findings, methodologies, contributions, and relevance of each research overview.

Year	Main Points	Reference
2015	The Green Bay, Wisconsin Metropolitan Sewerage District reduced electricity consumption by 50%, saving 2,144,000 kWh annually, through the implementation of energy-efficient blowers. In Albert Lea, Minnesota, a WWTP installed a 120 kW microturbine CHP system, saving approximately USD 100,000 annually and reducing energy usage by 70% due to lower electricity, fuel expenses, and maintenance costs. In Switzerland, energy analyses conducted on two-thirds of WWTPs led to an average cost reduction of 38%. A domestic WWTP with aerobic-activated sludge and anaerobic digestion utilizes 0.6 kWh m^{-3}, with over 50% of energy consumption attributed to aeration. Anaerobic digestion biogas can meet 25–50% of energy needs, and additional modifications can further reduce energy requirements.	[70]

Table 24. *Cont.*

Year	Main Points	Reference
2016	The energy performance of WWTPs cannot be universally characterized by a single Key Performance Indicator (KPI). Several factors significantly influence energy performance, including plant size, dilution factor, and flow rate. Additionally, technology choice, plant layout, and geographical location contribute to the variability in energy performance among WWTPs. These elements collectively lead to the significant differences observed in the energy efficiency of WWTPs.	[110]
2017	The study offers a comprehensive examination of global energy consumption in WWTPs, delving into diverse technologies and emphasizing the pursuit of energy self-sufficiency. It underscores the significance of international benchmarking to enhance energy efficiency, acknowledging regional disparities stemming from varying technologies and effluent quality targets. Optimal energy efficiency is highlighted as paramount in WWTP design, with many facilities leveraging biogas derived from anaerobic digestion for heating and electricity generation. Additionally, some integrate renewable energy sources into their systems. However, despite the feasibility of these approaches, challenges persist, particularly in developing nations.	[111,112]
2018	Aeration stands out as the predominant energy consumer in WWTPs, often surpassing 50% of total energy usage. Control systems such as Ammonia vs. Nitrate (AVN) and Ammonia-Based Aeration Control (ABAC) have proven effective in reducing energy consumption, with potential downtime for blowers exceeding 25% while still maintaining effluent standards. Technological advancements, particularly in nitrogen removal pathways, offer the possibility of cutting aeration energy requirements by over 60%. To move towards energy neutrality, WWTPs are increasingly focusing on enhancing on-site energy production through anaerobic digestion and biomethane utilization with CHP engines. Pre-treatment of sludge emerges as a significant opportunity, potentially increasing energy output by up to fivefold. Additional strategies include the co-digestion of organic waste and on-site renewable energy production, with the potential to double biogas production and further contribute to energy self-sufficiency.	[113]
2023	Optimizing operational parameters, including adjustments to DO levels, Sludge Retention Time (SRT), and Mixed Liquor Recirculation (MLR), can lead to a significant reduction in energy consumption, typically in the range of 7–9%. The implementation of Total Nitrogen (TN) online monitoring at influent and effluent points has been shown to improve TN treatment efficiency by 1%, resulting in a 5.6% reduction in energy consumption and a 12.7% decrease in carbon emissions. Furthermore, upgrading to magnetic suspension centrifugal blowers can yield notable benefits, including a reduction in aeration energy ranging from 15% to 24%, accompanied by a decrease in the carbon footprint by 4.6–7.7%. Utilizing prediction models to forecast energy consumption one month in advance has been shown to lead to a 2.2% reduction in energy usage. Furthermore, co-digestion practices have demonstrated significant benefits: Co-digesting 7% fat with sewage sludge increased biogas output by 17%. Addition of fat-oil-grease (FOG) to low-strength wastewater resulted in a boost in energy production by 0.08 kWh/m^3. Incorporating carbonated soft drinks into the digestion process increased biogas production by up to 191%. Introduction of 3% glycerol led to an 81% increase in biogas production. Utilization of grease trap water increased biogas production by up to 209%.	[114]

An exploration of the energy and water requirements of water supply, WWT, and power generation systems, along with a critical assessment of their potential for achieving self-sufficiency in both energy and water, was presented by Gude [70]. As an example, the Green Bay, Wisconsin Metropolitan Sewerage District, serving over 217,000 residents with two treatment plants, successfully implemented energy-efficient blowers in its aeration system. This initiative resulted in a notable 50% reduction in electricity consumption, equating to a savings of 2,144,000 kWh per year. In Albert Lea, Minnesota, the WWTP implemented a 120 kW microturbine CHP system, leading to annual energy cost savings of approximately USD 100,000. The plant achieved an impressive 70% reduction in energy usage, primarily due to decreased electricity and fuel expenses, with additional savings attributed to reduced maintenance costs. In Switzerland, two-thirds of WWTPs have undergone energy analysis, resulting in an average cost reduction of 38%. Typically, a domestic WWTP employing aerobic-activated sludge treatment and anaerobic sludge digestion technology consumes 0.6 kWh of energy per m^3 of wastewater treated. Of this, approximately 50% or more of this energy is dedicated to electrical consumption for providing air to the aeration basins. In comparison, different WWT methods, such as lagoons, trickling filters, activated sludge, and advanced WWT, require 0.09–0.29, 0.18–0.42, 0.33–0.60, and 0.31–0.40 kWh m^{-3}, respectively. Anaerobic digestion-produced biogas has the potential to fulfill 25–50% of the energy needs for aerobic-activated sludge treatment, and further plant modifications to the plant may significantly reduce overall energy requirements.

Table 25. Strengths and opportunities identified in the mentioned case studies.

Authors	Strengths	Potential Advancements
[70]	Thorough examination of energy consumption throughout water supply, WWT, and power generation systems.	Opportunity for further research and practical validation of the proposed strategies.
[110]	In-depth coverage of literature on energy efficiency and monitoring methods for WWTPs.	Opportunity to develop specific strategies for achieving energy self-sufficiency.
[111,112]	Introduction of alternative strategies for achieving energy self-sufficiency in WWTPs.	Opportunity for additional research and verification in real operating conditions.
[113]	Extensive exploration of technologies aimed at reducing energy consumption in WWTPs.	Opportunity to conduct further research to validate the effectiveness of proposed measures under practical circumstances
[114]	Comprehensive review of practices aimed at achieving zero greenhouse emissions in WWTPs.	Opportunity to develop specific techniques for achieving zero emissions.

According to Longo et al. [110] no single KPI universally characterizes energy performance. The main point is that the analysis of a substantial data sample provided evidence regarding the influence of factors such as plant size, dilution factor, and flow rate, with technology choice, plant layout, and geographical location identified as significant contributors to the observed large variability.

Gu et al. [111,112] offer a comprehensive overview of energy consumption in WWTPs, exploring various technologies implemented globally. The study delves into the potential for achieving energy self-sufficiency in these plants, emphasizing international benchmarking to enhance understanding of energy efficiency. This is crucial given the variations in energy consumption across regions due to diverse plant technologies and effluent quality objectives. While ongoing efforts exist in this field, optimizing energy efficiency has become integral to the design and construction of WWTPs, with a significant focus on developing energy self-sufficient facilities. Currently, most energy self-sufficient WWTPs utilize biogas generated through anaerobic digestion of sludge for tasks such as digester heating and electricity production. Some cases also incorporate renewable energy sources such as wind, solar, and hydroelectric power. Despite the feasibility of energy self-sufficiency in WWTPs, challenges persist, particularly in developing nations.

According to Maktabifard et al. [113], aeration typically accounts for the largest share of total energy consumption in these plants, often exceeding 50% of the total. Control systems like AVN and ABAC have demonstrated significant potential for energy reduction, achieving more than 25% downtime for blowers while meeting wastewater effluent standards. Additionally, technological upgrades, particularly in nitrogen removal pathways, have shown the ability to reduce aeration energy needs by over 60%. The next step towards achieving energy neutrality involves increasing on-site energy production, with anaerobic digestion and biomethane production coupled with CHP engines being efficient methods for recovering the chemical energy in raw wastewater. Sludge pre-treatment methods could further enhance energy production by up to five times. While these steps may not be sufficient for complete energy neutrality, additional electricity demand could be met through organic waste co-digestion and on-site renewable energy production, potentially doubling biogas production in the case of organic waste co-digestion.

Maktabifard et al. [114] presented a systematic review of various practices aimed at achieving net-zero carbon WWT. N_2O mitigation strategies primarily target (i) optimizing aeration mode and DO set-point, (ii) preventing DO gradients through mixing optimization, (iii) avoiding NH^{4+} peaks, (iv) preventing NO_2 accumulation, and (v) ensuring complete denitrification by providing adequate carbon sources or enhancing hydrolysis in primary clarifiers. The optimization of key operational parameters such as DO, solids retention time (SRT), and mixed liquor recirculation (MLR) significantly influences the aeration system and electricity usage in bioreactors. Adjusting SRT, DO, and MLR could lead to a 7–9% reduction in energy consumption. Additionally, implementing TN online monitoring equipment at both influent and effluent points, along with a carbon source dosing system, improved TN treatment efficiency by 1% while reducing energy consumption and carbon emissions by 5.6% and 12.7%, respectively. Upgrading traditional blowers to magnetic suspension centrifugal blowers resulted in a 15–24% decrease in aeration energy and a 4.6–7.7% reduction in Carbon Footprint (CF). Moreover, employing prediction models to forecast energy consumption one month in advance led to an estimated 2.2% reduction in energy usage at WWTPs. Co-digestion is proposed as a simple method to enhance macronutrient balance, adjust moisture levels, and dilute inhibitory or toxic substances, thereby positively impacting energy production and reducing CF. In developed countries, many energy-neutral plants recover biogas through co-digestion. For instance, co-digesting 7% fat with mixed sewage sludge increased biogas output by 17%. Utilizing fat-oil-grease (FOG) for co-digestion with low-strength wastewater can boost energy production by 0.08 kWh m^{-3}, whereas the total energy requirement for the studied plant was reported as 0.32 kWh m^{-3}. Incorporating carbonated soft drinks as a co-substrate increased biogas production by up to 191%, while adding 3% glycerol as a co-substrate resulted in an 81% increase. Similarly, using grease trap water as a co-substrate led to a biogas production increase of up to 209%. Many co-digestion plants have achieved 100% energy neutrality or even become net energy positive, including Zurich Wedholzli WWTP in Switzerland (42 GWh per year), Point Loma WWTP in the US (193 GWh per year), Grevesmuhlen WWTP in Germany (193 GWh per year), and Sheboygan Regional WWTP in the US (32 GWh per year).

The reviewed papers offer a comprehensive evaluation of strategies and technologies designed to enhance energy efficiency and achieve self-sufficiency in WWTPs. A notable positive aspect highlighted across these studies is the identification of various operational measures and technological advancements that can significantly reduce energy consumption in WWTPs. Effective strategies include aeration control optimization, anaerobic digestion combined with CHP generation, and advanced sludge pre-treatment methods. These approaches show promising results in both reducing energy usage and increasing on-site energy production. Additionally, the studies provide valuable insights into the potential for achieving energy self-sufficiency in WWTPs by integrating renewable energy sources such as biogas, wind, solar, and hydroelectric power.

Examples of successful implementations, such as those at the Green Bay Metropolitan Sewerage District and the Albert Lea WWTP, demonstrate the feasibility and benefits of these initiatives. The papers also highlight the importance of benchmarking approaches and data analysis in assessing energy performance and identifying opportunities for improvement in WWTPs. By comparing different benchmarking methods and synthesizing energy consumption data, the studies contribute to a deeper understanding of the factors influencing energy efficiency. However, the reviewed papers also address several challenges and limitations. Achieving complete energy neutrality remains complex, especially in developing nations where technological and financial constraints can significantly hinder progress and make room for improvements.

Cost-effectiveness, environmental protection, and technology adoption remain significant barriers to the widespread implementation of energy-efficient practices in WWTPs. Overall, while the studies highlight promising strategies and technologies for improving energy efficiency in these facilities, further research, investment, and collaboration are essential to overcome existing challenges and fully realize the potential for energy self-sufficiency in WWT.

6. Conclusions

Numerous approaches have been investigated to optimize energy consumption and foster sustainability within WWTPs. Theoretical models employing algorithms to simulate energy consumption reductions have been proposed, alongside suggestions for integrating various technologies such as CHP units, hydroelectric plants, and PV systems. Additionally, recommendations have been put forth for replacing current equipment with more energy-efficient alternatives or augmenting them with additional equipment, such as inverter units. Furthermore, comparative evaluation methods between different WWT units and the energy management practices of individual WWTPs have proven effective in generating improvement pathways. These approaches have demonstrated promising results, with energy consumption reductions exceeding 10% in some cases, primarily through strategies such as optimizing aeration strategies and equipment. The integration of renewable energy sources like biogas and solar power, and implementation of advanced control systems, can also lead to a greater reduction in energy consumption. Specifically, techniques such as flow modeling, simulation, and redesign of aeration facilities have led to a significant reduction in energy requirements for aeration, which is typically the largest energy consumer in WWTPs. The full use of biogas produced through anaerobic digestion as well as the use of solar photovoltaic systems create conditions for WWTPs to achieve energy self-sufficiency or even become clean energy producers. Finally, the adoption of advanced control algorithms, such as fuzzy logic controllers and database-driven optimization models, enables more efficient operation of WWTPs' processes, resulting in significant energy savings.

Utilizing techniques like flow modeling, simulation, and facility redesign, WWTPs have achieved significant improvements in energy efficiency. Efforts to predict energy consumption over WWTP lifecycles provide valuable insights for sustainable management practices. Growth models and scenario-based optimization approaches empower engineers to anticipate infrastructure utilization and evaluate operational costs, facilitating long-term efficiency planning. Additionally, comparative evaluations have identified critical barriers to operational efficiency across various regions, offering guidance for improving municipal wastewater management. Theoretical studies delving into energy self-sufficiency highlight the significance of optimal parameter selection and multi-generation setups in achieving sustainable outcomes. Factors like turbine inlet temperature and dissolved oxygen levels are pivotal in optimizing efficiency within WWTPs. Despite persistent challenges such as data limitations and regional specificity, innovative approaches spanning from dynamic optimization algorithms to the integration of renewable energy sources present promising avenues for attaining energy savings and system optimization.

In conclusion, these findings collectively underscore the significance of continuous research and collaboration in advancing energy efficiency and sustainability within the WWT sector. By leveraging insights from modeling, simulation, and comparative evaluation, stakeholders can strike towards more resource-efficient and environmentally friendly practices, ultimately contributing to a cleaner and healthier environment for future generations. Moreover, future research endeavors should prioritize examining the economic sustainability of these methodologies and their applicability across diverse contexts, thereby addressing existing gaps in current studies. Finally, an area for exploration beyond these aspects could be the evaluation of the acceptance of the proposed methods by WWTP operators.

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Abbreviations

The following abbreviations are used in this manuscript:

ABAC	Ammonia-Based Aeration Control
AI	Artificial Intelligence
ATAD	Autothermal Thermophilic Aerobic Digestion
AVN	Ammonia vs. Nitrate
AWWTPs	Advanced Wastewater Treatment Plants
ASP	Activated Sludge Process
BIC	Bayesian Information Criterion
BOD	Biochemical Oxygen Demand
CANON	Completely Autotrophic Nitrogen Removal Over Nitrite
CBOD	Carbonaceous Biochemical Oxygen Demand
CEPT	Chemically Enhanced Primary Treatment
CF	Carbon Footprint
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
DC	Direct Current
DO	Dissolved Oxygen
DRT	Dryer Residence Time
EEMs	Energy-Efficient Motors
EU	European Union
FBF	Fluidized Bed Furnace
FOG	Fat-Oil-Grease
GHG	Greenhouse Gas
GWh	Gigawatt-hour
HEXs	Heat Exchangers
KPI	Key Performance Indicator
kWh	Kilowatt-hour
kWh g^{-1}	Kilowatt hour per kilogram
MLR	Mixed Liquor Recirculation
MWh	Megawatt-hour
N_2O	Nitrous Oxide
NO_3	Nitrate
$N\text{-}NH_4$	Ammonium
NO_2	Nitrite
PE	Population Equivalent

PID	Proportional-Integral-Derivative
PI	Precipitation
PLC	Programmable Logic Controller
PV	Photovoltaic
Qin	Influent flow rate
RES	Renewable Energy Sources
SAF-MBR	Staged Anaerobic Fluidized Membrane Bioreactor
SBR	Sequencing Batch Reactor
SCADA	Supervisory Control and Data Acquisition
SEG	Seine-Grésillon
SHTR	Steam Heat Transfer Rate
SS	Suspended Solids
SRT	Solids Retention Time
TDP	Total Dissolved Particles
TFB	Turbulent Fluidized Bed
TN	Total Nitrogen
TSP	Total Suspended Particles
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket Reactor
USA	United States of America
UV	Ultraviolet
VFDs	Variable Frequency Drives
VSDs	Variable Speed Drives
WWTP(s)	Wastewater Treatment Plants
WWT	Wastewater Treatment
WWTWs	Wastewater Treatment Works

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