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Methodology for Energy Optimization in Wastewater Treatment Plants. Phase I: Control of the Best Operating Conditions

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Abstract: Most purification systems work correctly from the point of view of water quality; purification, like any industrial process, must also be carried out efficiently with a minimization of costs. The overall project examined the potential benefits of using a recommended methodology for process evaluation and energy optimization in the aeration stage of activated sludge in the biological reactor at wastewater treatment plants (WWTP), which accounts for more than 44% of total operating costs. This energy control methodology encompasses the process, the installation and the control system. These three phases are examined in separate articles to make it easier to guide the user in the arduous task of optimizing energy efficiency of the WWTP from start to finish. This article focuses on Phase I of the methodology, the stage in charge of selecting the correct variables to control the best process conditions in the activated sludge system of the WWTP. Operating conditions that are a function of the recommended sludge age are influenced by exogenous factors such as temperature. The implementation of a real-time control system of the selected process variables, adapted to the needs, achieves reductions in the overall energy consumption of the installation, in this phase alone, of more than 15%, by reducing the oxygen requirements of the system and the recirculation ratios.

Keywords: WWTP; activated sludge; energy optimization; energy consumption; operating conditions; control system

1. Introduction

Urban wastewater treatment involves a series of energy-intensive processes with significant margin for improvement in terms of its energy footprint. In Spain, in recent decades, energy consumption associated with urban wastewater treatment has increased greatly due to several factors. First, the increase is due to the 20% increase in the Spanish population over the last three decades [1]. Second, to a greater extent, it is related to the increase in the number of wastewater treatment plants (WWTPs). Finally, regulatory changes, in particular the implementation of the Water Framework Directive (WFD), Directive 2000/60/EC [2], which significantly increased the areas declared sensitive due to the risk of eutrophication and, therefore, the need to eliminate nutrients, resulted in an increase in the associated energy expenditure., At present, the energy consumption of WWTPs can represent an important part of the energy consumption of the different phases of the integral water cycle (IWC) installations, as happens for example in the Community of Madrid where it accounts for 59.1% [3], and 1% of the national energy consumption [4].

The historical evolution in the design of WWTPs goes from an almost exclusive objective of complying with the discharge limit values imposed by the regulations for the characteristic pollutants of urban wastewater, to introducing, in an imposed way, in the design process the concept of energy consumption, sustainability and self-sufficiency as important variables. For all these reasons, it is of vital importance to have purification systems and operating strategies that minimize the impact that human activity generates on the quality of the water in the receiving natural environments and, therefore, on the associated ecosystems; it is becoming increasingly important that the purification of wastewater is developed in a sustainable way from an energy point of view, through the use of installations designed with energy efficiency as one of the important design variables. For this reason, the study of energy consumption in wastewater treatment and of some of the current trends to improve efficiency and increase the degree of energy self-sufficiency in WWTPs is of interest.

If we also consider fundamental aspects such as:

- the increase in the price of electricity by more than 50% in the last 10 years for industrial consumers in Spain [5],
- high energy dependence in Spain and the EU27 with the need to import almost 75% of the energy consumed,
- the slow evolution of energy savings in the water supply and treatment sector [6],
- the increasing demands of regulators for the quality of reclaimed water, with a tendency to reach drinking water levels that require the application of more complex and advanced technologies with higher energy consumption [7].
- and the United Nations Sustainable Development Goals (SDG), with targets that Member States have agreed to pursue by 2030 [8].

All this leads to growing economic, social and administrative pressures to improve energy efficiency at all levels. In wastewater management, it is necessary to increase the interest of agencies, public services and wastewater treatment plant operators in the application of benchmarking procedures [9]. This is considered a crucial approach for achieving energy objectives and contributing at a local and national level to the goals of SDG 6 primarily and indirectly to the goals of SDG 11, SDG 12, SDG 13, SDG 14 and SDG 15, by reducing operating costs [10] and mitigating global warming [11].

Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU, and repealing Directives 2004/8/EC and 2006/32/EC [12], was adopted to provide mandatory regulation for European Union (EU) member states, with a view to promoting energy efficiency within the EU and establishing concrete actions to achieve the expected energy savings. These directives led to several measurements, including the setting of general and national targets for energy use and the obligation to carry out regular energy audits [13]. Therefore, given the centrality of the water-energy nexus, this article will focus on energy efficiency as one of the priority areas of the European Commission and the UN, and will be one of the main elements addressed in the forthcoming Water Directive [14].

An example of this growing awareness also in the wastewater sector is ENERWATER [15], a project funded by the European Commission aimed at developing a standard methodology for assessing and improving energy efficiency in wastewater treatment. On the other hand, on 25 September 2015 an ambitious and transformative project was carried out at the UN in which the Heads of State and Government and high representatives of different countries met with a common objective: reaffirm the World Summits already established in the UN Rio Declaration on Environment and Development, the World Summit on Sustainable Development, the World Summit on Social Development, the Programme of Action of the International Conference on Population and Development, the Beijing Platform for Action and the United Nations Conference on Sustainable Development [8].

The above idea laid the foundation for a new era of sustainable development through the promulgation of 17 goals or targets, henceforth SDG, that will encourage action for 15 years in five key areas: people, the planet, prosperity, peace and partnerships. In this way, the new Agenda 2030 for Sustainable Development was created, promoting the prosperity of both people and the planet. It emphasized that these goals will be a continuation of the previous ones, in which the 17 new SDG goals will take on the Millennium Development Goals and expand them [16]. SDG 6 "Clean Water and Sanitation" focuses on the idea that we must achieve improved integrated water resource management at all levels to ensure water availability and sanitation for all and its sustainable management and sets six targets to achieve this.

For all these reasons, a methodology is needed for energy optimization of the biological processes necessary for water purification. The objective of this article is to present the first phase of the proposed methodology, which focuses on the optimization of the organic matter degradation process in the biological reactor, pending the presentation of two further phases focusing on the optimization of the installation and the control system. The methodology is based on the analysis of the successful experiences at the WWTP of San Pedro del Pinatar in the Region of Murcia (Spain), during the period between 2011 and 2014, in achieving the most efficient management of wastewater treatment processes and carrying out energy and technical audits that encompassed the process, the installation and the control system. This methodology will contribute efficiently to achieving SDG 6 and, in parallel, to making cities and human settlements inclusive, safe, resilient and sustainable (SDG 11) by 2030.

2. State of the Art

2.1. Energy Consumption in WWTPs

Energy management as a separate discipline began to evolve after the first oil shock in 1973 and came into effect after the second one in 1979, when real energy prices rose dramatically. Although improving energy efficiency has been a key issue for industry, trade and governments, it was in 2010 that energy efficiency policy began to grow globally, and a few years ago efforts were being made to achieve a level of efficiency that was truly meaningful worldwide and at all levels.

A comparative evaluation on the unit energy consumption of WWTPs in different countries demonstrated that the unit energy consumption, expressed as the energy consumed per cubic metre of treated water, kWh/m^3, should be considered in energy efficiency studies. However, this study variable does not consider the pollutant load of the influent, so the results of the studies may be biased by influents that are especially diluted, by receiving high ratios of rainwater, or especially concentrated for any other reason. A priori it seems logical to propose a variable that agglutinates both the treated flow and the pollutant load, such as the inhabitant-equivalent (h-e), defined by Directive 91/271/EEC [17] as the biodegradable organic load with a 5 day biochemical oxygen demand (BOD_5) of 60 g of oxygen per day. The study by Albaladejo-Ruiz and Albaladejo-Falcó [18] concluded that kWh/h-e is the variable that best allows prediction of the energy consumption data of WWTPs according to their size. However, perhaps due to the inertia of the studies carried out previously or because the h-e variable is an adoption derived from European regulations that may not be applied or may not be applied in the same way in all regions of the planet, most of the studies use kWh/m^3 as the study variable, so it will be used to express the results obtained in our study of energy optimization.

Until the end of 2010, the specific consumption of electrical energy, expressed as the energy consumed per cubic metre of treated water, for this type of installation was 0.5–0.7 kWh/m^3 of treated water, values collected in energy consumption studies [19], with the stage of aeration of the active sludge being the one that contributes most to overall energy consumption, representing between 50 and 70% [20].

At a regional level, different studies have been carried out in Spain on the energy consumption of wastewater treatment plants (WWTPs). Simón et al. [19] studied the energy consumption of 90 WWTPs in the Region of Murcia, most of which were composed of activated sludge (AS) systems in prolonged aeration with nitrogen elimination and 58% with tertiary treatment systems for water reuse, and concluded that their average unit consumption was 0.55 kWh/m^3. Albaladejo-Ruiz and Albaladejo-Falcó [18] also studied 538 WWTPs from the Valencian Community and the Region of

Murcia, mostly formed by AF systems in prolonged aeration with nutrient removal processes (mainly nitrogen) and tertiary regeneration treatments, concluding that the average unit consumption of the WWTPs in the region was 0.43 kWh/m^3. Ferrer et al. [3] concludes that the average unit consumption of the WWTPs of the Community of Madrid was 0.33 kWh/m^3.

At a national level, the Institute for Energy Diversification and Saving [4], through an estimate based on the installed power in all WWTPs, considers that the average unit consumption of urban wastewater treatment in Spain is 0.67 kWh/m^3. Hardy et al. [21] indicate that the unit energy consumption of WWTPs in Spain is 0.53 kWh/m^3 ranging from 0.41 kWh/m^3 to 0.61 kWh/m^3, and the Spanish energy consumption associated with the urban water cycle corresponds to 3.9% of national energy consumption and the energy consumption associated with wastewater treatment corresponds to 0.9%.

The publication by Gu et al. [22] compiles data from different authors on the unit energy consumption of WWTPs in different countries: 0.52 kWh/m^3 in the USA [11], between 0.40 kWh/m^3 and 0.43 kWh/m^3 in Germany [11], 0.31 kWh/m^3 in China [11], between 0.079 kWh/m^3 and 0.41 kWh/m^3 in South Africa [11], 0.243 kWh/m^3 in South Korea [23], 0.42 kWh/m^3 in Sweden [24], 0.52 kWh/m^3 in Switzerland [25] and 0.304 kWh/m^3 in Japan [26]. And finally, the report realized by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [27] states that worldwide the unit energy consumption of WWTPs varies between 0.62 kWh/m^3 and 0.87 kWh/m^3.

After an exhaustive investigation of the state of the art, partial investigations were found on how to save energy through the implementation of control systems and optimization of energy consumption in WWTPs [28], by optimizing a specific stage such as aeration, by means of an expert adaptive predictive system (ADEX) [29] and/or comparative analysis of aeration technologies [30], by parameterization of energy consumption in treatment plants [18], by energy analysis of processes [31,32], by detecting energy co-generation possibilities [33], by optimizing maintenance tasks such as cleaning diffusers with formic acid [34] and by improving oxygen transfer [35].

Many of the contributions found come from experiences carried out in the Region of Murcia where the treatment of wastewater is a priority due to the vital importance of water in this territory, both to protect our water environment and to have a basic resource to develop agricultural activity, one of the main sources of wealth in the region. After designing a General Sanitation and Purification Plan in 2001, all the infrastructures foreseen in it have been executed in Murcia, which currently has more than 116 sanitation and purification installations and 57 pumping facilities that generate more than 105 hm^3/year, serving more than 99.4% of the population of the Region of Murcia. The investment that has been carried out in the Region has cost more than €650 million, only in treatment plants and general collectors, according to data provided by the Water Sanitation Entity of the Region of Murcia (WSERM).

However, little documentation was found on the systematic step-by-step methodology that can be followed to achieve global energy optimization of a wastewater treatment facility, with the ultimate goal of reducing costs and emissions of gases into the atmosphere. Some research was found on methodologies for the control of wastewater treatment plants [36] and, very recently in 2018, as it was commented previously, a European project [15] for the development of a standard methodology to evaluate and improve energy performance in WWTPs arose. This study started with an installation with a quite high specific energy consumption, around 1 kWh/m^3 of treated water, so there was a great interest, on the part of WSERM and the company in charge of managing the operation and maintenance of the treatment plant, to reduce energy costs, and continue advancing the knowledge and application of advanced technologies for savings. Part of these proposals were collected in the final degree project by Lozano et al. [37] and now they are developed as a step-by-step methodology for energy optimization with the idea that can be extrapolated to any facility. This methodology would be in line with the European objective of the 2011–2020 Energy Saving and Efficiency Action Plan [38], which contemplates a series of actions aimed at reducing energy consumption and costs in all economic sectors by means of energy efficiency actions, with the aim of meeting the objectives established by

Europe of 20%, thus, together with the greenhouse gas emission reduction objectives approved at the 2007 Spring European Council, which seeks a sustainable, economic service with minimum impact on climate change, a priority and global problem for our society.

Not forgetting the revision of the European energy strategy, Energy Strategy 2030, in which the initially proposed objectives are extended to a 40% reduction in greenhouse gas (GHG) emissions and a 27% increase in energy efficiency (a target that can be revised in 2020 to raise it to 30%) [39,40].

2.2. *Starting Energy Conditions at the San Pedro del Pinatar WWTP*

The WWTP of San Pedro del Pinatar (Murcia, Spain) incorporates an integrated system of an activated sludge biological reactor with ultrafiltration membranes that allows not only a guaranteed quality of the effluent, but also a significant reduction in the volume of the reactor. The plant was built over the previous facility on a site approximately 9000 m^2 in size, located on the border of the San Pedro del Pinatar Regional Salt Marsh and Dune Park, and was designed to treat a flow of 20,000 m^3/day of wastewater, with the aim of serving an equivalent population of 130,000 inhabitants. However, from the end of its commissioning to the operating period during which the project was conducted (2011–2014), no treatment flows of more than 10,000 m^3/day were recorded. Figure 1 shows that the flow values received at the facility during the experimental period, represented by a yellow bar graph, were considerably lower than those expected in the design, represented by a red line with a linear trend. Figure 2 shows the load received by the WWTP expressed in kg/day of the different pollutants such as Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorus (TP), and the temperature (T), which vary seasonally, and which are also, except in specific periods, lower than those expected in the design. These parameters have a significant influence on the electricity consumption of the installation, situating the average specific consumption of the WWTP at around 1.03 kW/m^3, before initiating actions to minimize energy consumption.

The new San Pedro del Pinatar WWTP, in Murcia, began to be built in 2005 to replace the old WWTP existing in this municipality, which was built in the 90s and whose treatment capacity was insufficient, especially in the summer season in which the maximum population is recorded, and which also presented significant operational deficiencies. The construction of the San Pedro del Pinatar wastewater treatment plant doubled its treatment capacity, under the expectation of treating the flows of wastewater from the construction of new urbanizations and increased influx of tourists, forecasts that were not met.

In 2008 a real estate crisis began, which spread throughout the period studied, and the installation was oversized.

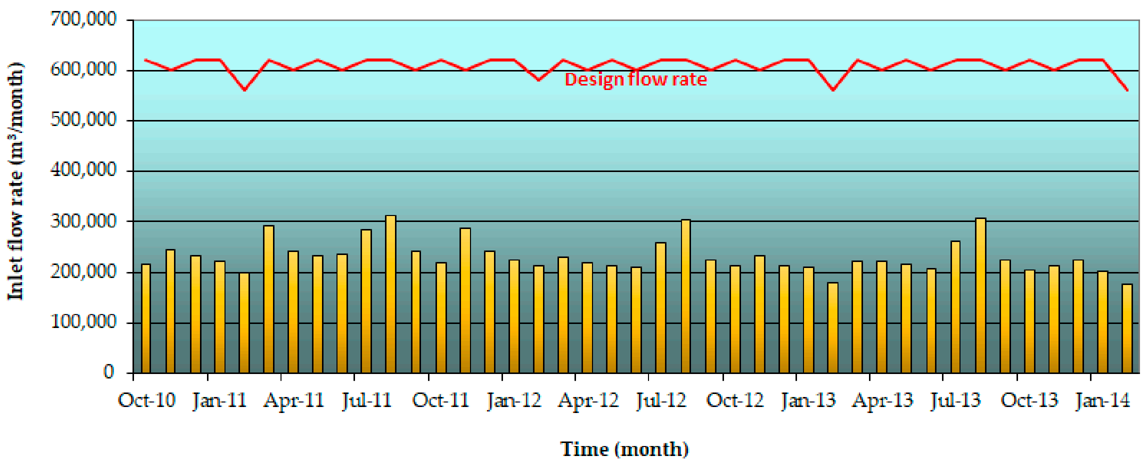

Figure 1. Evolution of the biologically treated inlet flows to the WWTP (Q).

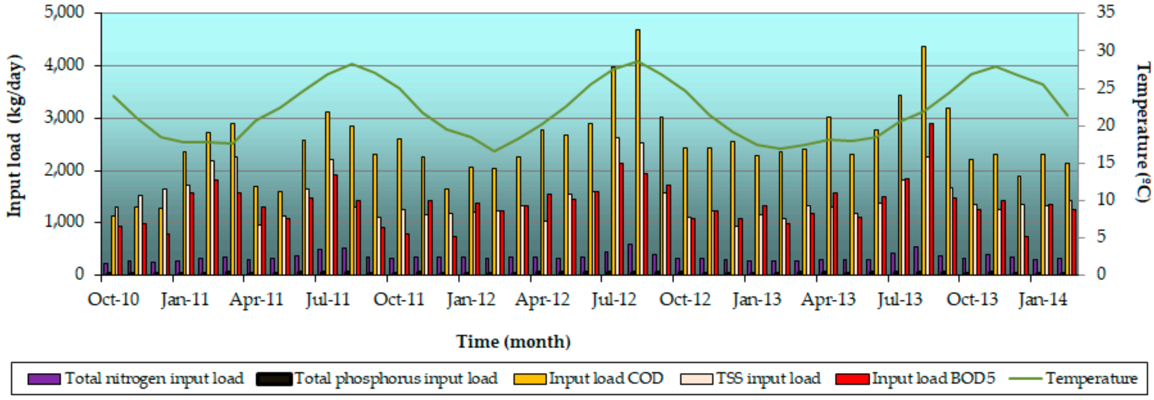

Figure 2. Evolution of the received pollutants (BOD_5, COD, TSS, TN, TP and T).

Figures 3 and 4 show, respectively, the monthly values of energy consumption, expressed in kWh, and the specific energy ratio, expressed in kWh/m^3 of treated water, of the municipal WWTP of San Pedro del Pinatar registered during 2011.

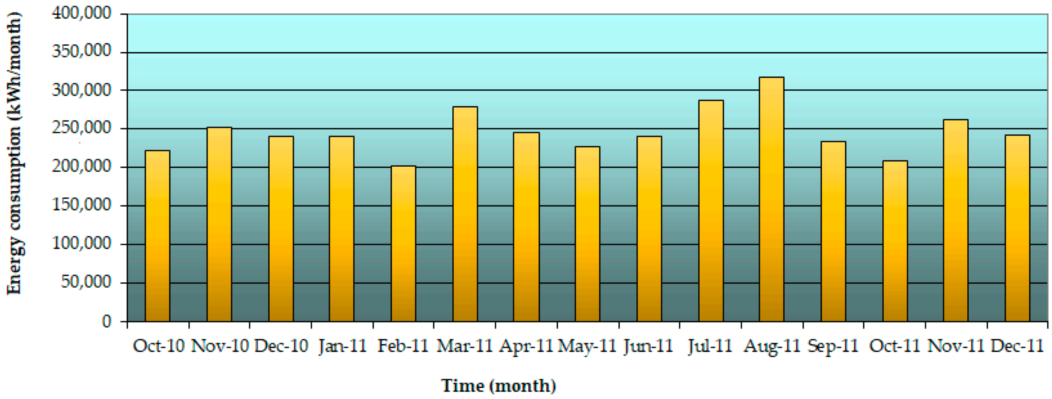

Figure 3. Evolution of energy consumption.

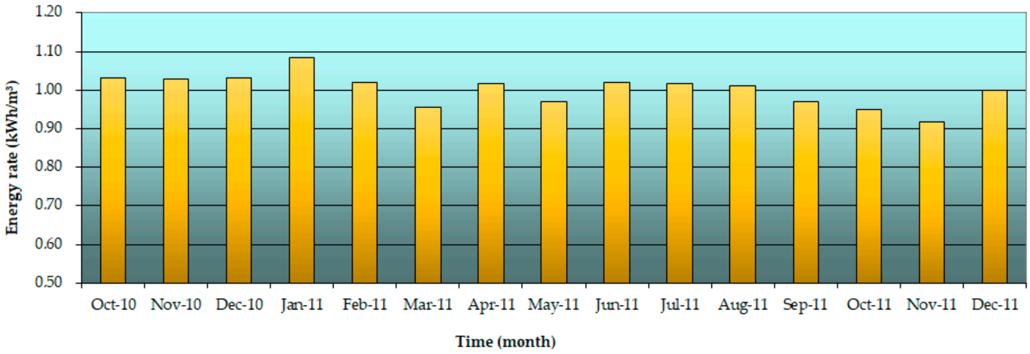

Figure 4. Evolution of initial specific consumption expressed in kWh/m^3.

These values are substantially higher than the average specific consumption values of WWTPs with conventional biological treatment, which are around 0.5 kWh/m^3, which means an electricity consumption of 2225 GWh/year for all facilities, according to data published in the National Energy Efficiency Action Plan 2017–2020 [8].

All this further justifies the importance of optimizing energy consumption in installations with membrane biological reactor (MBR) technology, and it was during 2011 when the energy consumption data for the different stages of the WWTP were collected, which served as the basis for the optimization trials.

The size of a WWTP is a variable that exponentially affects its unitary energy consumption, due to the synergies associated with economies of scale [18]. Therefore, installations that are oversized, because they are designed with robustness criteria or because they are built under unfulfilled future forecasts (e.g., a real estate bubble) have high energy consumption. It should also not be overlooked that the effects of economies of scale also apply to other operating costs, such as employee labor costs, product costs and general costs, and therefore, from an economic point of view, wherever possible, there should be a tendency to build WWTPs that bring together the highest possible flow of wastewater.

For all these reasons, it is considered necessary to include the exponential ratio of the unitary energy consumption of WWTPs with respect to their size as one more variable to be considered in hydrological planning, so that the implementation of new WWTPs is carried out with sustainable environmental criteria from a global point of view and not exclusively with hydrological criteria, due to the positive environmental effect generated by the decrease in unitary energy consumption, both in atmospheric pollution and in the contribution to Global Warming and Climate Change [41].

3. Materials and Methods

3.1. Study of the Specific Energy Consumption in Each of the Individual Stages of the WWTP

The general objective of an efficiency study is to identify how to reduce the consumption of products and services in the operation of a WWTP, maintaining the quality of the treated water within the values established in the application legislation [17] and/or discharge permit granted to the WWTP, the efficiency in the elimination of contamination parameters (BOD_5, COD, TSS, TN, TP, etc.) and the safety of the operation. Therefore, an energy efficiency study must study the use of the energy resources in the WWTP, which are above all electrical energy, and must consider the distribution of electrical consumption in each of the stages of the WWTP.

The study was carried out by monitoring and tracking the electrical parameters provided by the network analyzers installed in each of the control and command centres of the San Pedro del Pinatar WWTP for a whole year, 2011. The installation of the analyzers was carried out in a sectorized manner, so that each of them collected the energy consumed in a different phase of the purification process (pre-treatment, biological treatment by activated sludge (AS), biological treatment by membranes, dewatering, etc.).

The analysis of daily records of energy consumption readings provided by network analyzers and automatic records of consumption stored in the Supervisory Control and Data Acquisition (SCADA) application allowed abnormal situations of overconsumption to be detected and to identify exactly where they occur. The results obtained for the electricity consumption parameters, collected daily in the different stages, over a period of one year, are recorded for analysis in circular diagrams included in Section 4.1 of results.

In a generalized manner, and as has been commented previously, energy efficiency studies have established the unitary energy consumption, expressed as the energy consumed per cubic metre of treated water, kWh/m^3, as a variable to consider and show that the biological aeration stage of this WWTP represents the most significant percentage, more than 38% of its total energy consumption. This led us to study each of the elements that make up the biological treatment stage, in order to detect critical points and aspects that could be improved.

3.2. Analysis of the Installation and the Main Elements of the Activated Sludge Aeration System

The biological treatment applied at the San Pedro del Pinatar WWTP consisted of prolonged aeration through a process of activated sludge with biomembranes (Figures 5–7).

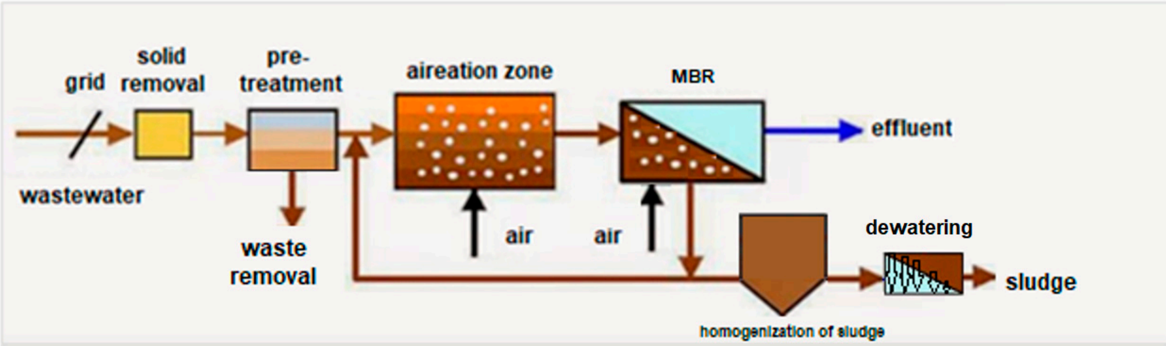

Figure 5. General purification scheme with aerobic biological reactor and membrane biological reactor [42].

Figure 6. Biological reactor with air distribution network.

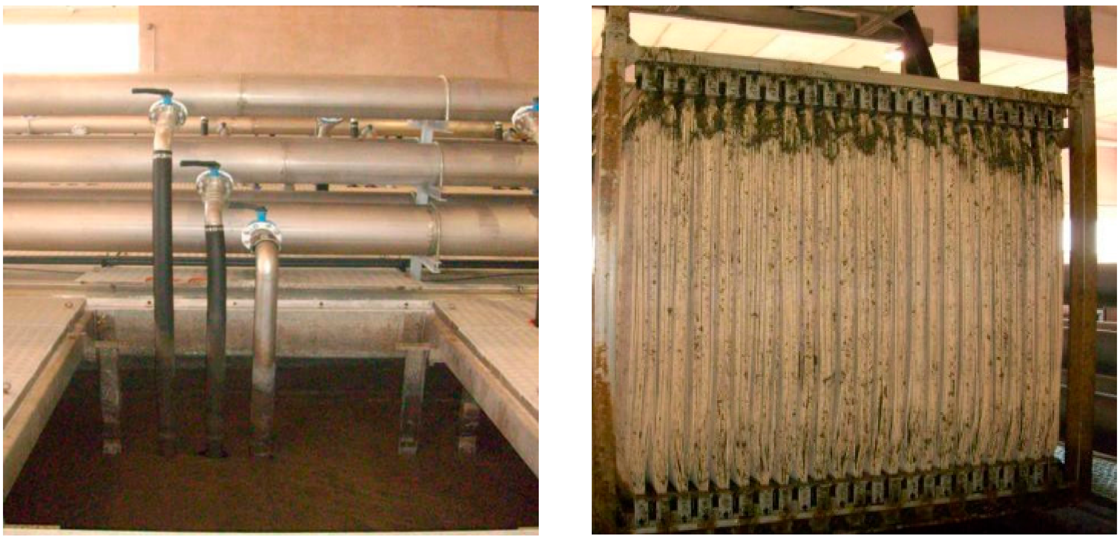

Figure 7. Membrane cassette with aeration and permeation ducts.

The biological treatment consisted of two plug-flow reactors. Each of the two lines had a volume of 8015 m^3, resulting in a total biological reactor volume of 16,030 m^3. Each reactor had dimensions of 25 m * 58 m and a depth of approximately 5.7 m. It was divided into four zones: one anoxic (representing 21% of the total volume) where the denitrification phenomenon takes place and three aerobic (each representing 26.3% of the total volume). As this is a process with prolonged aeration, there is the additional condition of establishing a sludge age that allows a stabilized sludge to be obtained.

The supply of air to the biological process was carried out by means of six MAPNER® blowers, model SEM.40 TRN.GCA with 3588 Nm^3/h unit flow at 0.67 bar. Two of these blowers were equipped with a frequency variator and the other four with all-or-nothing operation. Each oxidation channel had a motorized valve used to control the air supply to each of the biological reactors. A total of 2808 fine bubble diffusers (1404 per line) of the TFB-Flygt Sanitaire® type with a diameter of 9″ have been installed for air distribution in the biological reactor. In addition, it had an oxygen measurement analyzer per reactor.

On the other hand, the reactor had ten TFB-Flygt® submersible mixers model SR- 4650.410 SF with 5.5 kW of power. The objective of this equipment was to supply the minimum agitation during the period of low loads, when the specific contribution of air was less than the minimum advisable to produce a mechanical agitation by aeration. The elimination of phosphorus takes place biologically, without the need to dose a chemical product for "simultaneous precipitation" or "co-precipitation". A total phosphorus concentration at the outlet of less than 2 mg/L was achieved. The biological degradation process was completed with a membrane treatment system made up of Zeeweed 500D Polyvinyl difluoride (PVDF) hollow fiber modules of the Zenon® brand (1516 m^2 of installed membrane surface), which provides an effluent of excellent quality without the need of subsequent disinfection of the water.

The membrane biological reactor (MBR) had five MPR® SEM55 trilobular rotary piston blowers with a 75-kW motor, which provided enough air flow for cleaning the membrane surface, with a maximum instantaneous air flow per cassette of 425 Nm^3/h and a minimum flow per cassette of 272 Nm^3/h. The unit flow of air provided by each blower unit was 3200 Nm^3/h at 0.3 bar. No unit was equipped with an electronic frequency converter.

In order to maintain the appropriate concentrations both in the biological reactor, for the growth of the purifying microorganisms, and in the membrane chamber, to avoid incorrect operation, degradation and/or premature fouling, the system had 5 Flygt® LL3300.181LT-802 brand submerged pumps with a 37 kW motor for the external recirculation of mixed liquor from the membrane chamber to the anoxic chamber of the biological reactor. The installed equipment was of equal capacity, with a maximum flow rate of 1600 m^3/h and was equipped with two frequency variator units. All the equipment associated with the aeration stage installed in the WWTP of the municipality of San Pedro del Pinatar can be seen in Figure 8.

Figure 8. Aeration elements in San Pedro del Pinatar wastewater treatment plants (WWTP) with activated sludge (AS) + membrane biological reactor (MBR) technology.

Ordinarily, nitrogen removal is carried out biologically by nitrification of nitrogen compounds in the aerobic zone of the biological reactor and denitrification in a previous anoxic zone. In an activated sludge WWTP, such as the installation under study, the elimination of nitrogen involves the installation of an anoxic stage prior to the aerobic stage and the introduction of an internal recirculation current from the aerobic zone to the anoxic zone. Therefore, in general, the elimination of nutrients is a factor that increases the energy consumption of the WWTP, mainly due to the increase in aeration needs in the aerobic zone, related to the high oxygen demand of the nitrification process [3], but also due to the pumping needs of the internal recirculation current and the agitation needs of the anoxic zone.

3.3. Tests for the Energy Optimization of a Biological Treatment Process

The methodology followed for the energy optimization of the biological aeration stage covers all levels (process, equipment and control) and it was based mainly on (Figure 9):

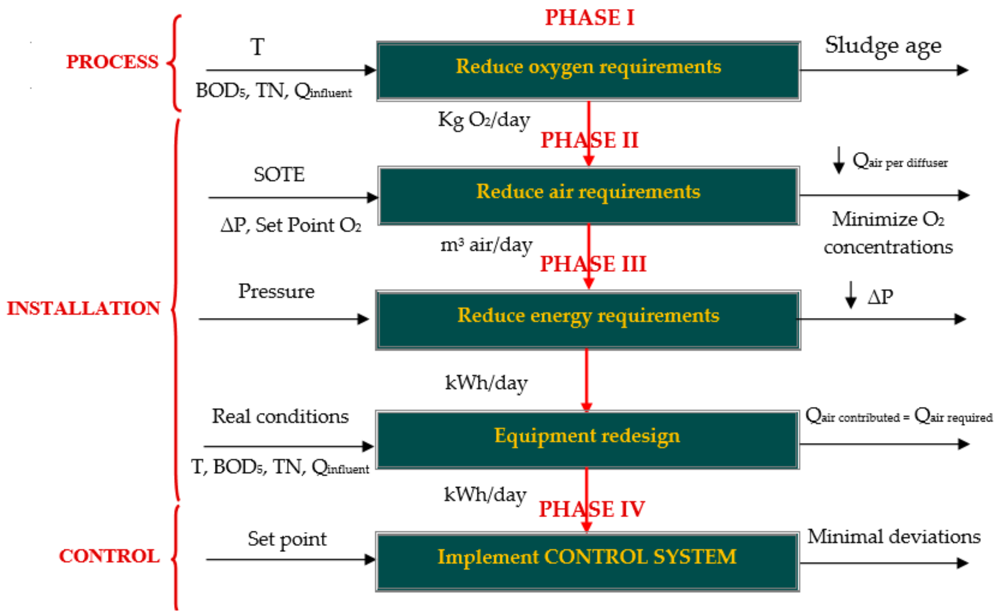

Figure 9. Stages included in an energy optimization of an aeration system [43].

where

$Q_{influent}$ is the inlet flow of wastewater to the biological reactor;
SOTE is the standard oxygen transfer efficiency;
ΔP is the pressure drop in air line and
Q_{air} is the flow of air injected into the biological reactor.

The objective of PHASE I was to create working premises to reduce the oxygen requirements of the system based fundamentally on working with a concentration of solids in the biological reactor or an age of the sludge, which will be a function of the temperature and will always be the lowest possible, but always ensuring the stabilization of the biological sludge.

Test 1: Selection of operating conditions to minimize oxygen requirements at source.

The control variables of the operating conditions in the most used biological reactors are based on the measurement of the mass load (Cm) and the measurement of the sludge age (Ef). Figure 10 shows an outline of the process variables that must be taken into account.

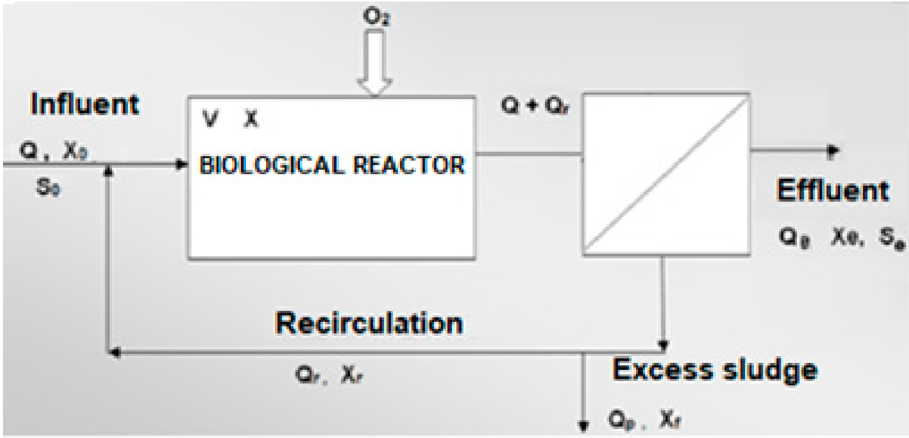

Figure 10. Biological reactor material balance diagram combined with MBR [44].

The mass load represents the relationship between the organic matter that enters the biological reactor daily and the mass of microorganisms contained in it according to Equation (1),

$$Cm = \frac{Q \times So}{V \times X} \quad (1)$$

where

Q is the inlet flow of wastewater to the biological reactor (m^3/h);
So is the BOD_5 input (mg/L);
V is the volume of the biological reactor (m^3) and
X is the concentration of the microorganisms in the reactor (mg/L).

The sludge age or cell retention time (Ef) represents the ratio, expressed in days, between the mass of microorganisms in the biological reactor and the mass of microorganisms removed from the reactor daily, and can also be expressed as a function of the mass load, see Equation (2),

$$Ef = \frac{V \times X}{Qp \times Xr} = \frac{1}{(0.2 \times Cm + Cm^{1.445})} \quad (2)$$

where

Qp is the excess sludge flow rate (m^3/d)
Xr is the concentration of microorganisms in the recirculation stream (mg/L) and
Xp is the concentration of microorganisms in the purge stream (mg/L) ($Xp = Xr$).

The sludge age must be calculated for each of the temperatures and phases in which the process will work and is necessary to guarantee the nitrification in the reactor and the organic elimination. The variability of the flow rate and the influent load to WWTPs makes it difficult to adjust the working sludge age, since the daily net production of solids in suspension in the mixed liquor (MLSS) varies constantly. This makes it necessary to perform daily analyses of suspended solids in the recirculation stream (RSS) and biological reactor content (MLSS) to modify the purge flow rate (Qp). Working with the mass load as a process control parameter in such variable conditions is a difficult task. However, the sludge age, as it does not depend directly on BOD_5 and influent flow, offers more stability to the process, while ensuring a minimum age for nitrification to take place completely.

The first effort to optimize aeration in the WWTP consisted of minimizing the oxygen requirements of the microorganisms, as well as the energy (kWh) required to transfer the oxygen necessary (kgO_2) to the mass of mixed liquor present in the biological reactor [36]. All this was within maximum and minimum safety values, and with the main objective of always adjusting the supply of oxygen to the instantaneous needs, eliminating excess or deficiencies of aeration that could trigger energy losses or non-conformities with the quality of the resulting water.

It should be noted that the oxygen demand from microorganisms results from the sum of the individual need for oxygen for the synthesis processes, the oxygen requirements for the elimination of nitrogenous matter and that required for the processes of endogenous respiration. As the first two factors are a consequence of the characteristics of the incoming water, the only thing that can be acted upon in order to minimize oxygen requirements is the consumption of endogenous respiration. This was achieved by minimizing the sludge age with which the reactor was working, in other words, the concentration of solids in the reactor [45].

If we also consider that San Pedro del Pinatar WWTP has a second biological treatment step formed by ultrafiltration membranes, the sludge age (Ef) is a key parameter in determining the tendency for fouling due to its repercussion on the concentration of solids within the membrane biological reactor and the presence of extracellular polymeric substances (EPS). Therefore, it was important to determine an optimum sludge age, in which the concentration of soluble EPS (fundamentally) was minimal and there was a sufficiently high oxygen transfer efficiency so that fouling could be controlled [46]. MBR should operate at sludge ages greater than 15 days. It is recommended to work with the minimum MLSS value that the system admits, depending on the contaminant load and the sludge age adopted for the expected yields [47]. The proper adjustment of sludge age in biological systems controls the degradation rate of the substrate, the concentration of MLSS and sludge production.

To achieve sludge age control, the excess sludge produced in the biological reactor was purged, and taking into account that for a complete mixing reactor with submerged membranes the concentration of solids in the reactor is equal to the concentration in the purge, the purge flow required to maintain a certain sludge age is defined by Equation (3), according to the process scheme shown in Figure 10.

$$Q_P = \frac{V}{Ef} \tag{3}$$

In most aeration plants the operators set a concentration and age of the sludge that are kept constant regardless of the biological reactor temperature; so far it has worked in this way. In the case of purification plants with MBR systems, the concentration recommended by the membrane manufacturer (7000 mg/L) made it necessary to maintain concentrations of mixed liquor in the biological reactor of around 5000 mg/L and air flows of around 2500 Nm^3/h.

However, this section evaluates the oxygen needs under these conditions and those obtained by working at a sludge age equal to the sludge age required for sludge stabilization [31], always using the rules and standards of dimensioning of single-stage activated sludge plants (ATV) as the calculation base [48], obtaining in each case the data shown in the figures included in the results section.

Test 2: Implementation of an automatic system to control optimal operating conditions.

Initially, the controls were complex algorithms designed to guarantee the final quality of the effluent and with instrumentation requirements that were difficult to achieve for WWTPs [49,50]. The need to comply with the discharge limits required by the regulations (91/271/CE and 2000/60/CE), the constant increase in water demand, the high cost of energy and the growing social pressure prompted new studies and projects to reach the current situation in which there are simpler advanced controls with less need for instrumentation, which facilitate the operation of WWTPs, guarantee compliance with the discharge limits and reduce energy consumption [51–59].

The advanced and intelligent control for energy saving presented in this methodology aims to achieve the best operating conditions by controlling sludge purge and recirculation, and to reduce energy consumption in purification processes. To do this it introduced two automatic control loops in the plant's Programmable Logic Controller (PLC) and SCADA, following the control flow diagram specified in Figure 11.

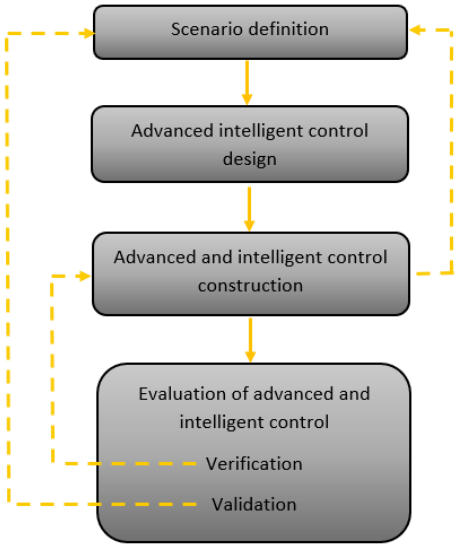

Figure 11. Methodology for the design and construction of an advanced and intelligent control [60].

➢ Automatic control system for sludge purging according to the sludge age.

Another aspect to be considered in order to reduce energy consumption in WWTPs is the optimization of pumping systems, in terms of the installation of more energy-efficient pumps, the installation of frequency variators and control systems for their operation, etc., which allows the pumping to operate under optimum conditions from an energy point of view. The study carried out by Ferrer et al. [3] on the Community of Madrid concludes that the installation of an advanced control system for pumping header would allow an estimated energy saving between 10% and 15% of the consumption of the pumping system. Studies carried out by Rosas [61] and Ferro et al. [62], in several Latin American countries, show that the replacement of pumps and motors and the implementation of frequency variators in pumping could lead to energy savings between 10% and 20% of the total consumption of the WWTP.

For all these reasons, when the sludge age measurement was selected as the control variable of the operating conditions in biological reactors that offers more stability to the process, a control loop was made that relates the daily net production of MLSS in the biological reactor with the excess sludge purge flow and the recirculation flow in order to maintain the recommended required concentration (Figure 12).

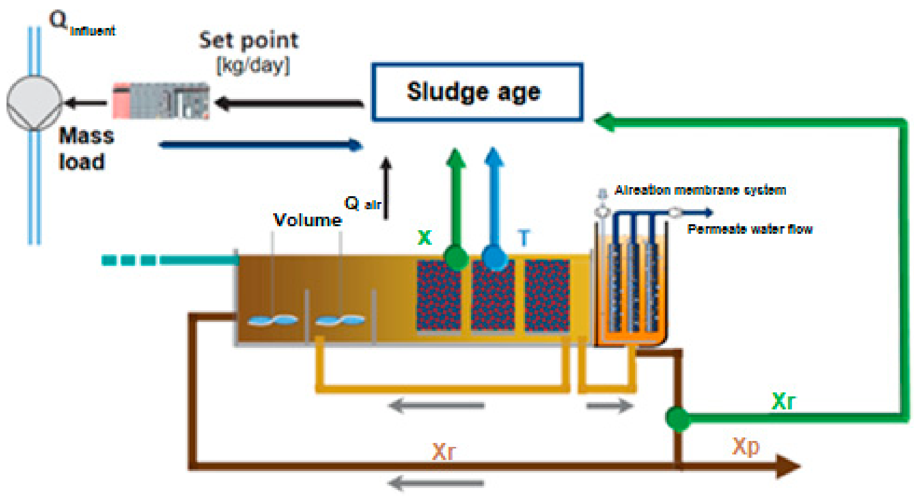

Figure 12. Closed loop control diagram.

The process was completed with the installation of two sensors for suspended solids measurement (HACH LANGE® SOLITAX model), one in the biological reactor, and the other in the excess sludge pipe. The readings of the solid sensor already installed in each of the membrane chambers in the MBR system, were also used. Both probes were connected to a HACH LANGE® SC200 model controller that continuously sent, via analogic signal (Figure 13), the value of MLSS and RSS to the PLC.

Figure 13. Solitax t-line solids immersion probe with SC200 controller.

The following signals were received in the plant SCADA for programming the control loop:

1. Excess sludge flow purged to the sludge homogenization tank, inlet to the dewatering equipment.
2. Concentration of solids in the biological reactor.
3. Concentration of solids in the sludge purge.
4. Concentration of solids in the MBR chambers to maintain the optimum minimum concentration for the correct functioning of the membranes.

The reactor temperature value was provided by the installation's dual oxygen concentration and temperature sensor, whose values were also recorded in the plant's SCADA.

Depending on these values, two control loops were programmed, which made it possible to work in two different ways, depending on the needs:

1. Maintaining a constant concentration of solids in the reactor. In this working mode, the SCADA will specify the desired working concentration. The control loop regulates the volume of sludge purged by adjusting the operating time of the pumps.
2. Keeping the sludge age constant. In this working mode the desired sludge age will be specified in the SCADA. The control loop will regulate the volume of sludge purged by adjusting the running time of the pumps.

➢ Automatic control system of the recirculation flow depending on the suspended solids.

Most conventional installations operate with a recirculation ratio of 100%, which corresponds in most cases to the maximum installed recirculation ratio. In the case of purification plants with MBR systems, the initial recirculation ratio is 400%, making it even more interesting to adjust it from an energy point of view. Working with the initial recirculation ratio means an electrical consumption of the recirculation and sludge in excess pumps of more than 12.0% of the total consumption of the biological treatment.

Therefore, working with the lowest concentration of solids in the biological reactor, adjusted to the plant's needs, and therefore with a concentration of solids in the membrane chamber within the permitted limits and without the danger of membrane surface clogging, favors the reduction of the mixed liquor recirculation coefficient at the reactor inlet from 400% to less than 200%. This implies a pumped flow reduction of 50%, ensuring the quality of the output water at all times (Figure 14).

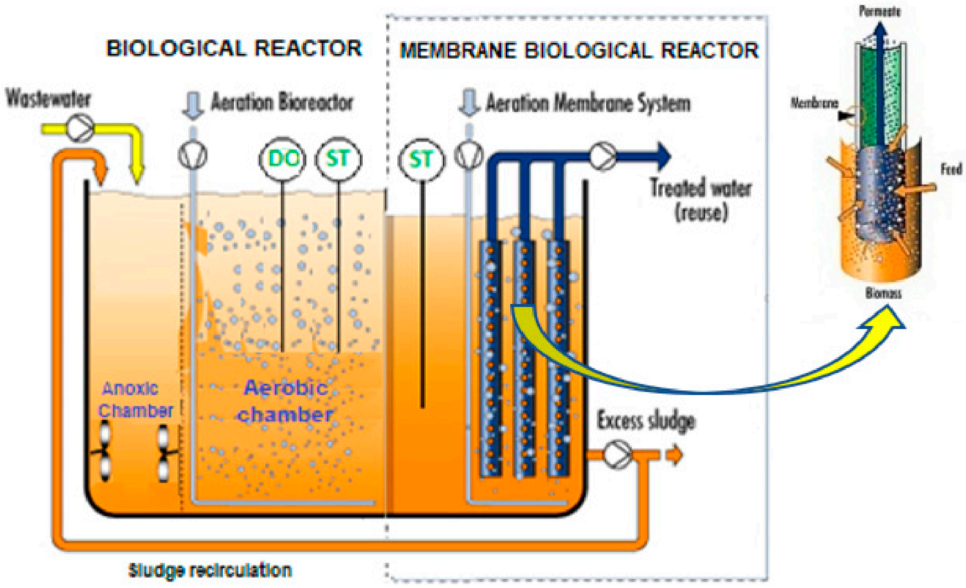

Figure 14. Control of solids in reactors by Solitax probes [63].

Two of the five recirculation pumping units installed were equipped with frequency converters whose operation was controlled by a proportional, integral and derivative controller (PID) regulation system that allowed two different modes of operation:

Mode 1: The recirculation of sludge is a direct function of the permeate flow filtered by the ultrafiltration membranes (Figures 15 and 16). For the calculation, the process scheme represented in Figure 10 is considered. The sludge recirculation flow is calculated with Equation (4):

$$Qr = R \times Q \rightarrow R = \frac{Qr}{Q} \tag{4}$$

where

Q is the inlet flow of wastewater to the biological reactor (m^3/d);
Qr is the recirculation flow rate (m^3/d) and
R is the recirculation ratio, configurable by the operator according to process needs.

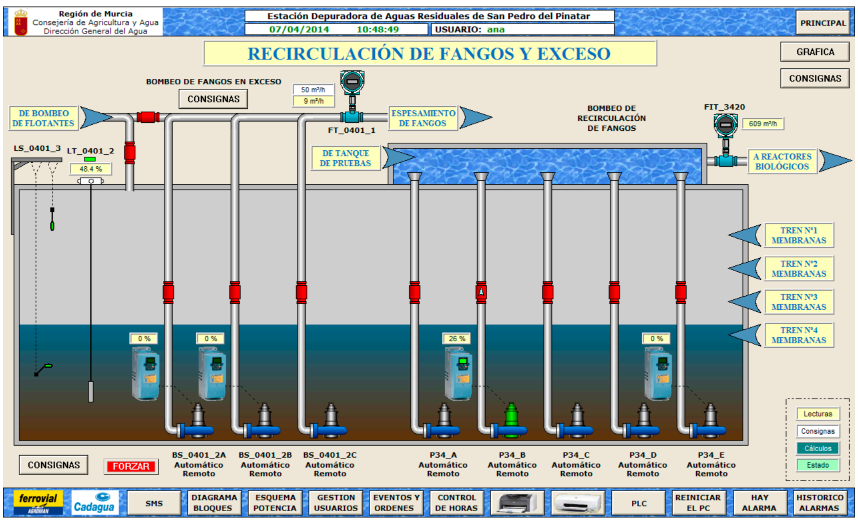

Figure 15. Control of sludge recirculation pumping as a function of the permeate flow through the membranes. Screenshot of the plant's Supervisory Control and Data Acquisition (SCADA) application.

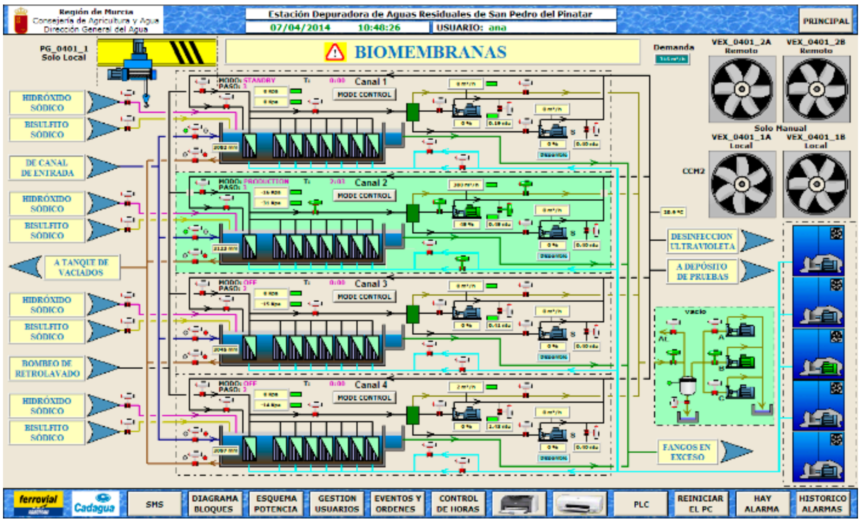

Figure 16. MBR system with measurement of permeate flow and concentration of solids. Screenshot of plant SCADA.

Mode 2: The sludge recirculation flow rate is a direct function of both the concentration of total suspended solids in the membrane chamber (to prevent fouling or improper operation of the membranes) and the concentration of biological reactor solids required for process stabilization (Figure 17).

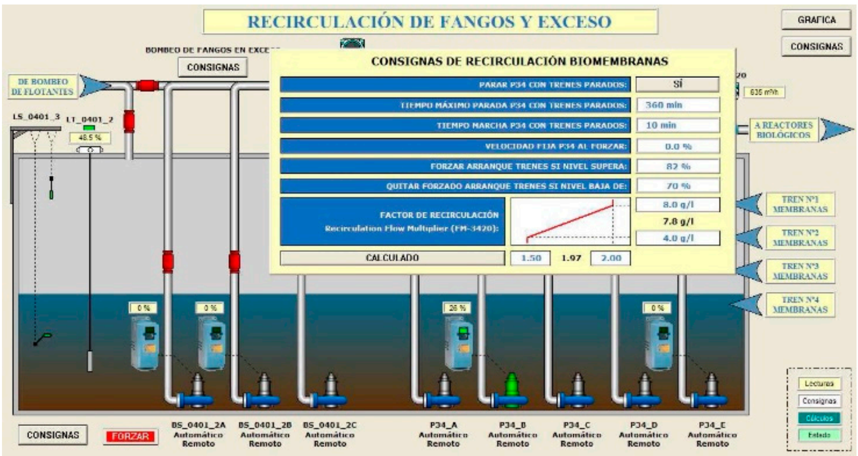

Figure 17. Control of sludge recirculation pumping as a function of the concentration of solids in the membrane chamber. Screenshot of plant SCADA.

According to the process scheme shown in Figure 10, if a balance of matter is carried out on the biological reactor in order to determine the relationship between the concentration of solids in the recirculation and the recirculation relationship itself, Equation (5) is obtained:

$$Xo \times Q + R \times Q \times Xr + Qp \times Xr = X \times [Q + RQ] \rightarrow con\ Xo \approx 0 \rightarrow R = \frac{(Q \times X - Qp \times Xr)}{Q \times (Xr - X)} \quad (5)$$

where

Xo is the concentration of micro-organisms in raw water or influent (mg/L);
X is the concentration of microorganisms in the biological reactor (mg/L) and
Xr is the concentration of microorganisms in the recirculation (mg/L).

Based on these conditions, if the recirculation flow is reduced as much as possible, the quality of the effluent is increased, in addition to reducing energy consumption [64]. When working with membranes, the quality of the outlet water is not so dependent on these conditions; however, the energetic aspect is important if it takes into account the very high recirculation ratios with which MBR works.

To control the concentration of suspended solids in the recirculation, the readings of the solid probes installed in each of the membrane chambers were used. They send a signal to the SCADA, with sufficient time to be able to act on the recirculation instructions in case the concentration of solids in the recirculation was too low (to cause the biological reactor to wash and/or the membranes to become clogged) or too high, which is far from the optimum energy point. If the probe readings moved away from the setpoint, an alarm signal would be transferred to the SCADA, with enough time to change the setpoints.

3.4. Study on Final Energy Consumption at the WWTP

Once the optimization tests were over, a monitoring and follow-up study of the electrical parameters were once again carried out, through the daily readings of the existing network analyzers in the WWTP and the automatic records of consumption stored in the application used for Supervision, Control and Data Acquisition (SCADA), as has already done in the initial study stage for the individual energy consumption of the installation. The results of the energy improvements achieved are expressed as energy ratio kW/m^3 and are recorded for analysis in a bar graph in the results section.

4. Results

4.1. Results of the Study of the Individual Energy Consumption of the WWTP

The percentage distribution of energy consumption of operations and processes [65] collected during 2011 was carried out. Figure 18 shows that energy costs represent more than one third of the operating costs of a WWTP. Therefore, when it comes to minimizing operating costs, special attention should be paid to energy consumption.

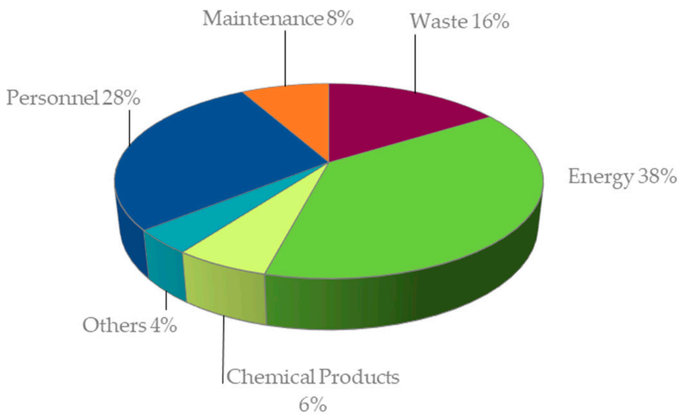

Figure 18. Distribution of WWTP costs.

The most important energy consumption is that derived from the biological process and secondly that derived from the operation of the MBR, responsible for the degradation of colloidal matter and dissolved matter in wastewater (Figure 19). Figures 20 and 21 show that the aeration stage of the biological stage produced in a plug-flow reactor and the aeration associated with the operation of the MBR, represent the most significant percentages of energy consumption. Therefore, the aeration stage accounts for approximately 68% of the energy consumption of the biological process and 53% of the operating consumption of the MBR; it can account for more than 15% of the overall costs of a WWTP and more than 38% of its total energy consumption.

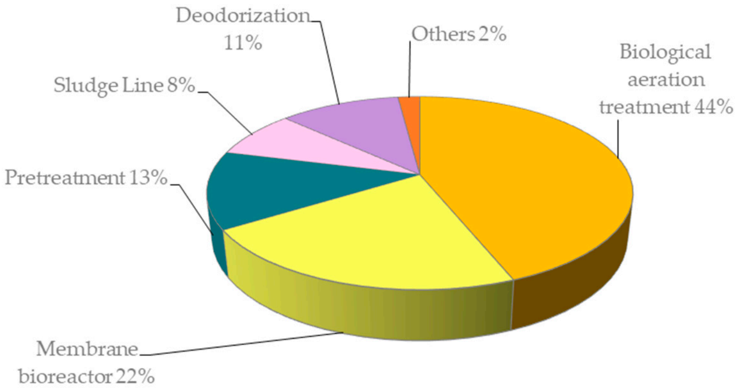

Figure 19. Distribution of energy consumption.

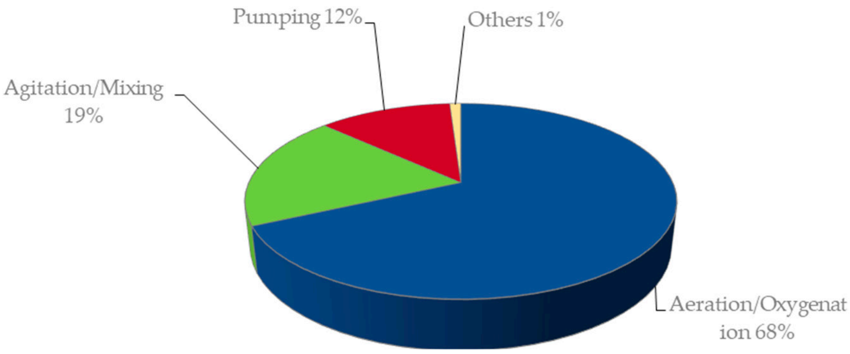

Figure 20. Distribution of energy consumption in biological treatment.

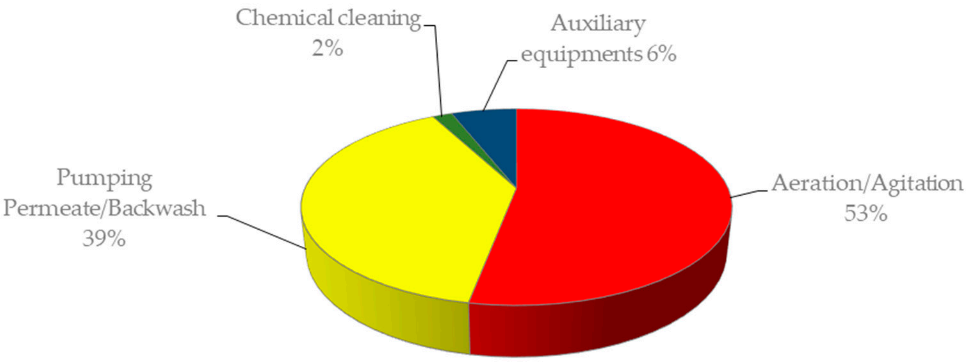

Figure 21. Distribution of energy consumption in the MBR.

4.2. Result of the Analysis of the Installation and Main Components of the Activated Sludge Aeration System

The critical points more susceptible to improvement and more relevant on which to act at the San Pedro del Pinatar WWTP are described below:

- High concentration of suspended solids in biological reactors. In an MBR up to 20–30 kg/m^3 [66] can be reached, although the optimum values of biomass concentrations for the MBR are between 8 and 12 kg/m^3 [45,67].
- High working sludge age.
- Recirculation coefficient equivalent to 400% of the water flow permeated by the membranes.
- Need to adjust oxygen requirements for stabilization.
- Optimization of air requirements.
- Study of operating conditions that may interfere with aeration efficiency.

The results obtained in the tests, developed in later sections, show that the initial values set by the membrane manufacturer have fallen far short of the values with which we are currently working.

4.3. Test Results for Energy Optimization of a Biological Treatment Process

Results of Test 1: Selection of operating conditions to minimize oxygen requirements at source.

For a concentration of suspended solids in the liquor mixture of the biological reactor of 5 g/L, air flows of around 2150–3120 Nm^3/h are required. These flows require working with a blower of 70% to 100% of frequency by acting on its frequency variator, using several units of the MPR® blower in summer (Figure 22).

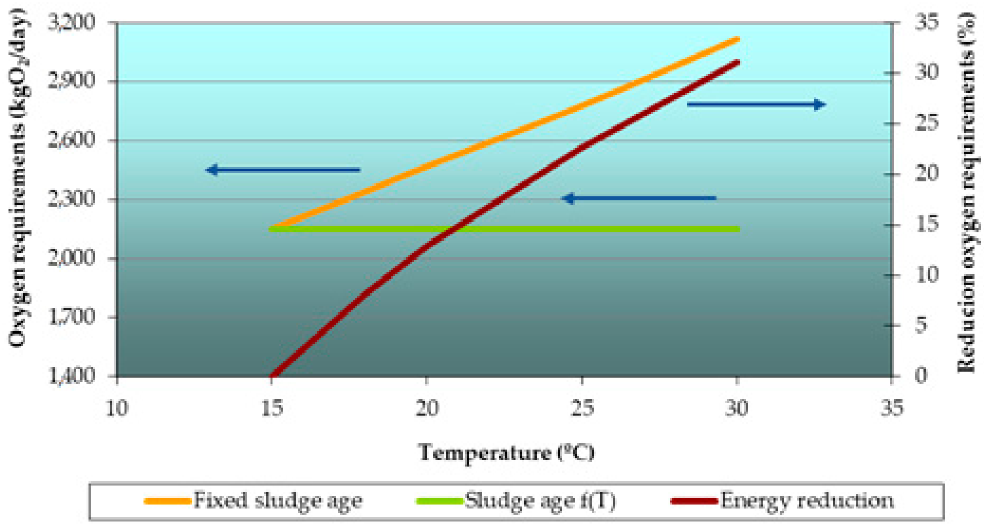

Figure 22. Reduced oxygen requirements when operating with a variable sludge age as a function of temperature (working concentration 5 g/L).

Due to the fact that the flows entering the WWTP and the concentrations of contaminants are much lower than those specified in the design, modifications are made in the concentration of suspended solids of the mixed liquor established, in 3 g/L the concentration in the membranes will be around 5 g/L (Figure 23). For one year this concentration remains unchanged without any alteration in the operation of the membranes (permeability values, transmembrane pressure, etc.) and in the quality of the effluent obtained, considerably reducing the range of air flows to 1750–2515 Nm^3/h for the purification process. In this case, an MPR® SEM55 blower is available that provides a minimum air flow of 2150 Nm^3/h which raises the need to acquire new aeration equipment.

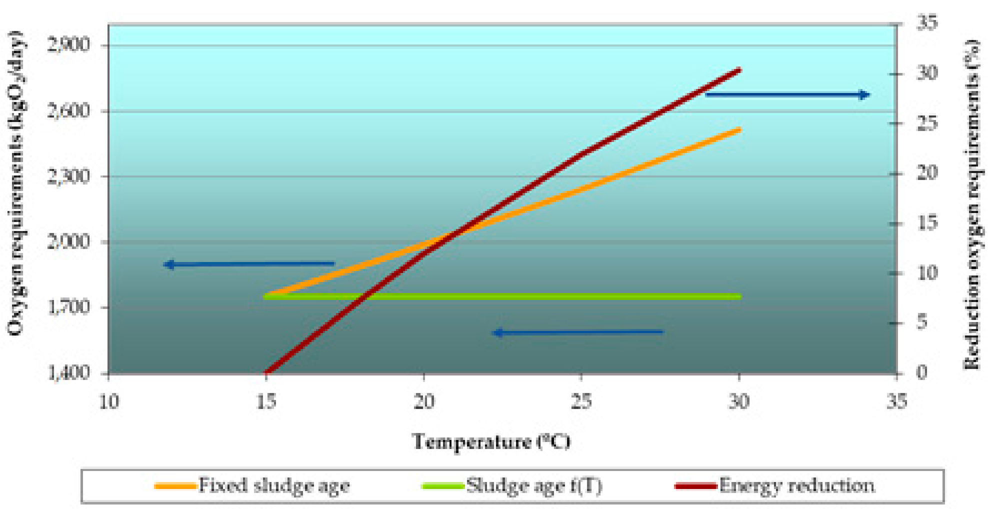

Figure 23. Reduced oxygen requirements when operating with a variable sludge age as a function of temperature (working concentration 3 g/L).

Figures 22 and 23 also show that while operating with a sludge age depending on temperature, the concentration of solids in the biological reactor decreased as the consumption of endogenous respiration, and therefore global energy consumption, was reduced, thus obtaining energy reductions close to 30% for the summer season. Similarly, it was observed that for an adequate control of oxygen consumption when working from 10 °C to 30 °C, the sludge age was reduced from 29 to 3 days and the concentration of solids had to be reduced from 4700 mg/L to 800 mg/L (Figures 24 and 25).

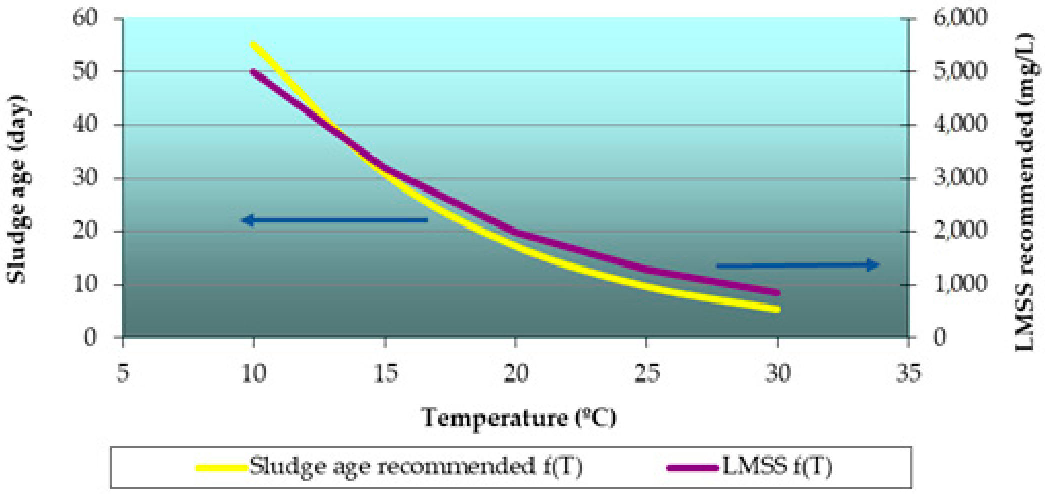

Figure 24. Variation of the recommended sludge age and concentration of solids in the biological reactor (LMSS) as a function of temperature (working concentration 5 g/L).

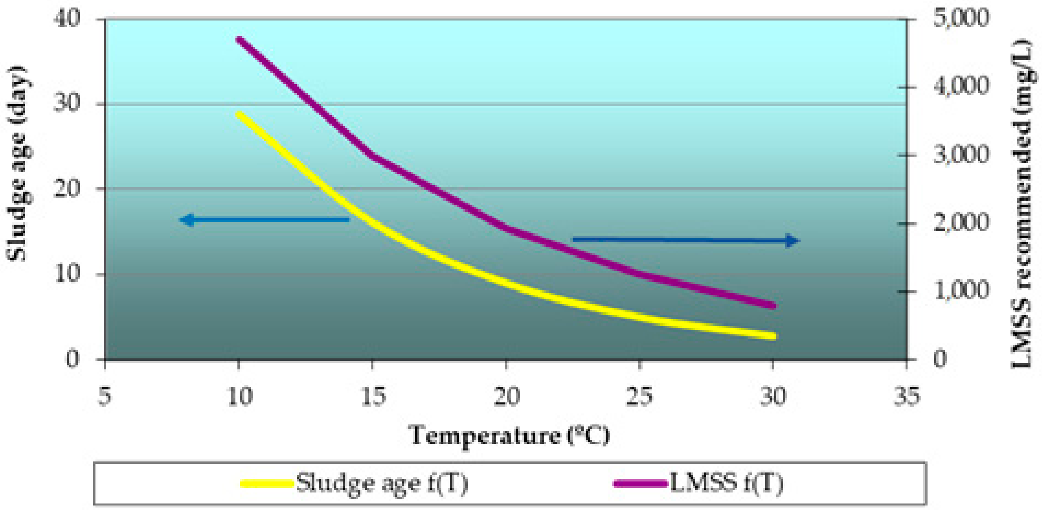

Figure 25. Variation of the recommended sludge age and concentration of solids in the biological reactor (LMSS), depending on the temperature (working concentration 3 g/L).

Finally, depending on the average temperatures recorded in the mixed liquor of the biological reactor during the different months of the year, the average annual reduction in energy achieved in the WWTP was evaluated, obtaining values of around 13%. Evidently, this decrease in electrical energy brought with it an increase in the production of sludge. In our case, the costs of global sludge management (including management, polyelectrolyte, water consumption and electricity) compensate for the energy costs associated with aeration of the biological process, so it will be appropriate to work with a sludge age depending on temperature (Figures 26 and 27).

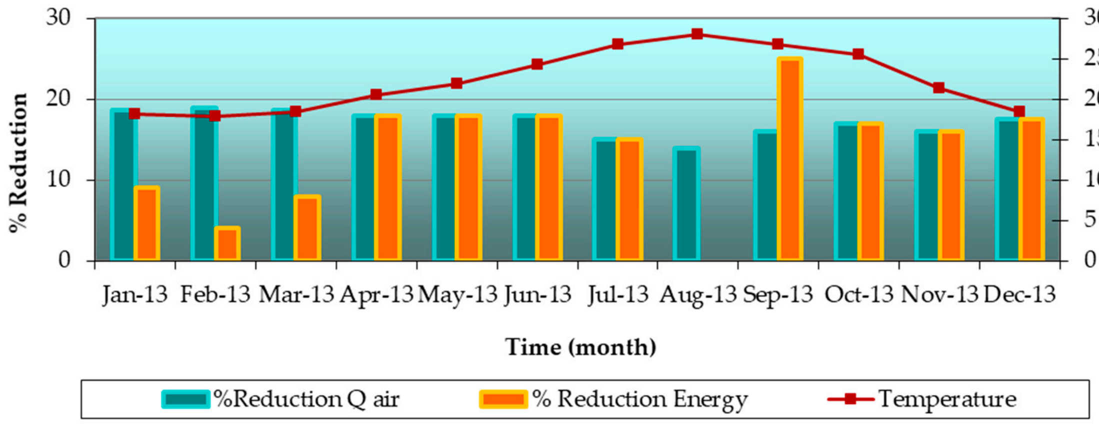

Figure 26. Percentage energy reduction function of the concentration in the biological reactor.

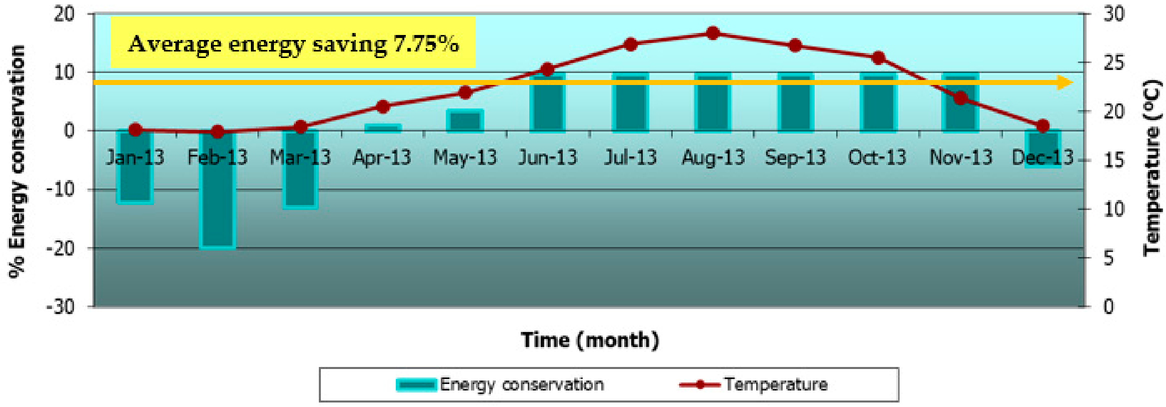

Figure 27. Average monthly temperatures and expected energy savings in the different months.

Results of Test 2: Implementation of an automatic system for the control of optimal operating conditions.

➢ Automatic control system for sludge purge depending on the age of the sludge.

The control system regulated in real time the amount of sludge to be purged, expressed in kg/day, in order to maintain the minimum sludge age required to ensure nitrification and stability of the biological process, ensuring energy savings of around 7.75%.

If the management of the operation can be carried out based on hourly periods with different tariffs, in such a way that the maximum possible energy consumption is shifted towards periods with cheaper tariffs, the consumption savings achieved can reach 10%. For this purpose, calendars with tariff periods and coefficients on energy and economy published on the website of the Iberian Market Operator (OMIE) [68] were used.

➢ Automatic control system of the recirculation flow depending on the suspended solids.

It is important to note that the membranes allow quite high concentrations of working solids, but there is a limiting factor that requires a minimum recirculation ratio to be maintained to achieve the recommended sludge age in the biological reactor, in order to prevent it from being washed and, on the other hand, to maintain a concentration in the membrane chamber that is not too excessive to avoid clogging.

It can be observed that as the recirculation ratio decreases, the concentration of recirculated sludge increases and the concentration in the membrane chamber increases. Concentrations in the membrane chamber no higher than 8 g/L and no lower than 4 g/L were used. The system was stabilized at recirculation ratios around 2, to be far from the sludge thickening limit; for recirculation ratios of less than 1.5, small variations in recirculation ratio values would cause a minor decrease in energy consumption, but considerable increases in the concentration of the (theoretical) recirculation sludge which could lead to membrane clogging, early fouling, etc. On the other hand, if the actual concentration that can reach the recirculated sludge is lower than the theoretical concentration, the washing of the reactor and the loss of solids in the effluent may start due to insufficient recirculation. From an energy point of view, reducing the recirculation ratio by 2 units, or 200%, means reductions in the energy consumption associated with this stage of close to 50%.

4.4. Result of the Study on the Final Energy Consumption of the WWTP

Considering the data with which this study started on the average specific consumption of the San Pedro del Pinatar WWTP, around 1.03 kW/m^3, the study on final energy consumption after the first phase of optimization of the proposed methodology leads us to energy ratio values around 0.83 kW/m^3 (Figure 28).

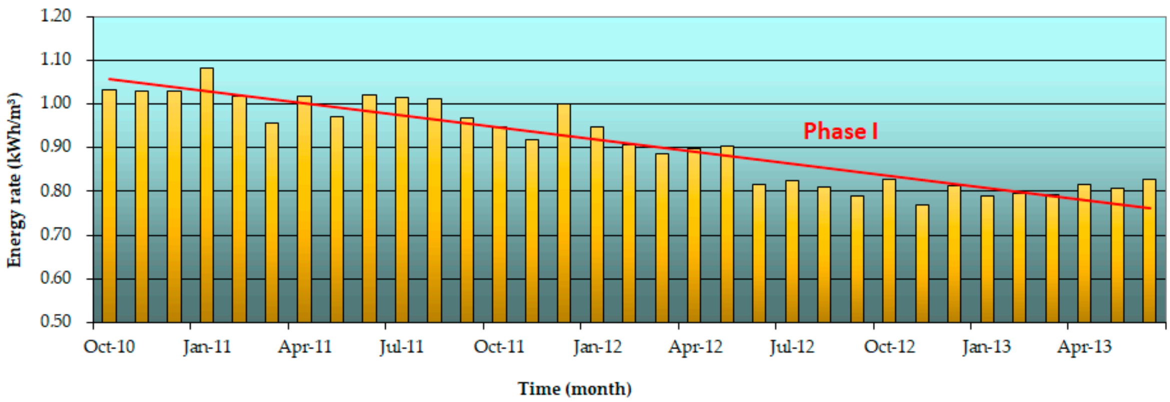

Figure 28. Evolution of specific consumptions expressed in kWh/m^3 throughout the Phase I energy optimization tests.

5. Discussion and Conclusions

Given the importance of energy reduction in WWTPs, it is considered essential to follow the methodology recommended for energy optimization, given that the objectives set for Phase I of optimization of the biological process of the San Pedro WWTP have been met. This methodology has been followed systematically in other treatment plants with excellent results, so it can be extrapolated.

The steps to be followed to find the optimum operating conditions have been defined, and the changes made in the installation and the improvement in the management criteria of the aeration process in WWTPs are shown. The implementation of advanced control systems for sludge flow and recirculated flow, which contribute to maintaining the ideal operating conditions pursued, mean additional energy savings, as well as more efficient management of processes.

The implementation of advanced control systems is being developed in a greater number of facilities, such as various WWTPs in Spain and Portugal, obtaining energy consumption savings in aeration between 15 and 20%, together with a 30% reduction in the concentration of nitrogen in the effluent and a 75% reduction in internal recirculation [69]. At the Galindo WWTP (1,500,000 h-e) the energy saving of the aeration system associated with the implementation of the control was 15% [70,71], and a subsequent adjustment of the blower impulsion pressure and an increase in the set point of the ammonium concentration from 1 mg/L to 2 mg/L obtained an additional saving of more than 11.3% of energy consumption [72].

The main conclusion that can be drawn from the first battery of tests carried out is that working at the lowest possible recommended sludge age, as a direct function of the temperature inside the biological reactor, achieves the stabilization of the biological sludge at all times. The introduction of automatic control loops allows an average energy saving of 7.75% by reducing the oxygen requirements of the system by 13%.

The implementation of an automatic sludge age control system using suspended solid probes installed in biological reactors allows an advanced management of the process to minimize the oxygen requirements of microorganisms at the source. In addition, it gives the aeration process stability by avoiding the excess or defect in the supply of oxygen required by the microorganisms, always maintaining an adequate concentration of microorganisms in the biological reactor. With the control system, an energy saving per tariff system is achieved, as it is possible through these programs to displace the energy consumption associated with aeration blowers and pumping towards the most economical tariffs.

From an energy point of view, reducing the recirculation ratio to values of 200% means reductions in energy consumption at this stage of close to 50%, which is the same as overall reductions in energy of around 6–8%. However, reducing the recirculation ratio further can cause excessive thickening of the sludge, causing clogging in the membranes, fouling, etc., while not causing excessive decreases in flow or energy consumption.

In conclusion, starting from an installation with energy ratio values higher than 1.03 kW/m^3, results of around 0.83 kW/m^3 are obtained in a first optimization phase. This means, with an average energy price of 0.11 €/kWh and an average treatment flow of 7000 m^3/day in the WWTP, an operating cost saving of 55,000 €/year and a reduction in CO_2 emissions of about 500 kg/year.

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Conflicts of Interest: The authors declare no conflict of interest.

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