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Economic Assessment of Energy Consumption in Wastewater Treatment Plants: Applicability of Alternative Nature-Based Technologies in Portugal

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Abstract: Understanding how to address today's global challenges is critical to improving corporate performance in terms of economic and environmental sustainability. In wastewater treatment systems, such an approach implies integrating efficient treatment technologies with aspects of the circular economy. In this business field, energy costs represent a large share of operating costs. This work discusses technological and management aspects leading to greater energy savings in Portuguese wastewater treatment companies. A mixed methodology, involving qualitative and quantitative aspects, for collecting and analysing data from wastewater treatment plants was used. The qualitative aspects consisted of a narrative analysis of the information available on reports and websites for 11 wastewater management companies in Portugal (e.g., technologies, treated wastewater volumes and operating costs) followed by a review of several international studies. The quantitative approach involved calculating the specific energy consumption (kWh/m^3), energy operating costs (EUR/m^3) and energy operating costs per population equivalent (EUR/inhabitants) using data from the literature and from Portuguese companies collected from the SABI database. The results suggested that the most environmentally and economically sustainable solution is algae-based technology which might allow a reduction in energy operating costs between 0.05–0.41 EUR/m^3 and 15.4–180.8 EUR/inhabitants compared to activated sludge and other conventional methods. This technology, in addition to being financially advantageous, provides the ability to eliminate the carbon footprint and the valorisation of algae biomass, suggesting that this biotechnology is starting to position itself as a mandatory future solution in the wastewater treatment sector.

Keywords: biotechnology; conventional wastewater technologies; economic sustainability; energy saving; microalgae technologies; wastewater

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Citation: Santos, E.; Albuquerque, A.; Lisboa, I.; Murray, P.; Ermis, H. Economic Assessment of Energy Consumption in Wastewater Treatment Plants: Applicability of Alternative Nature-Based Technologies in Portugal. *Water* **2022**, *14*, 2042. https://doi.org/10.3390/w14132042

Academic Editor: Cristina Sousa Coutinho Calheiros

Received: 12 May 2022
Accepted: 23 June 2022
Published: 26 June 2022

1. Introduction

Energy is the main operating cost of wastewater treatment. The North American Wastewater Treatment Plants (WWTPs) consume approximately 1–4% of the total energy production, and in Europe, the consumption is approximately 1% [1,2]. A financed project in the north of Portugal [3] identified the main energy consumers: the aeration equipment associated with biological treatment (58%), inlet pumping (9%), deodorization (8%) and sludge treatment equipment (6%). Assessing the efficiency of wastewater treatment plants (WWTPs) is essential for water service companies' survival and growth, as well as for correcting management procedures. In a circular economy framework, management involves the adoption of circular economy business models (CEBMs) that should lead to more economic and environmentally efficient and sustainable technologies.

Energy savings in WWTPs have been investigated in recent decades, but information on their operating costs is still scarce in the literature [4]. The focus is being placed on process optimization, rather than on cost-saving [2,5]. There is still a need for more information regarding nutrient removal, polishing treatments and operational costs of nature-based wastewater treatment technologies, as noted in studies [6–13]. Although there is a wide variety of chemical and biological technologies for nutrient removal, these processes normally entail high operational and investment costs that narrow profit margins. Thus, studies that shed some light on the comparison between operational costs of several wastewater technologies are critical for assessing the most efficient management of WWTPs.

Wastewater can be produced in different activities (e.g., domestic, urban, industrial, runoff, agricultural and sanitary landfilling), which can result in different physical, chemical and microbiological characteristics. Conventional WWTPs involve biological processes (e.g., activated sludge, biological filters, stabilization ponds, constructed wetlands and anaerobic digestion), chemical processes (e.g., chemical precipitation, electrochemistry and ion exchange), physical processes (e.g., ultrafiltration and ion exchange) or a combination of them. These conventional biological treatment processes need to address technical and high-cost limitations for obtaining the necessary removal of organic matter and nutrients. It is often necessary to include artificial aeration or chemical additions for improving treatments, which leads to high energy consumption besides being ineffective for carbon sequestration. By contrast, natural solutions based on constructed wetlands have proved to be very effective in removing organics and nitrogen, but still require energy consumption for effluent recirculation and evapotranspiration dependence [7,8].

In recent years, new microalgae-based technologies have been emerging for treating and reusing wastewater, involving one or more microalgae species or in consortium with bacteria colonised in photobioreactors (PBRs). PBRs include tanks, channels and lagoon/pond reactors. Microalgae consortiums are advantageous in removing organics, nitrogen and phosphorous through biodegradation pathways, assimilation and plant uptake, especially for a 1:5 microalgae: bacteria ratio [6] with fewer energy requirements (there is no need for external oxygenation or external carbon addition, since algae produce oxygen and bacteria produce the carbon needed for the consortium, acting also as a carbon sequestering system) [10]. In addition, in the scope of CEBMs, these technologies allow for added-value products from the valorisation of algae biomass (e.g., pigments, health products, feeding products, biofertilizers, biogas and biodiesel) [7,11].

Thus, there is an increasing interest in algae-based technologies for wastewater treatment, such as the high-rate algal pond (HRAP) systems [12], which can lead to a good removal of organics and nutrients from wastewater and the production of algae biomass that can be valorised. However, there are not many studies on HRAP operating costs and their comparison with ones of conventional technologies, especially regarding the population equivalent (p.e.) and volumes of treated wastewater. HRAPs are shallow ponds (typically between 30cm and 50cm), where wastewater circulates through a low-power paddle wheel, producing high algae biomass and nutrient removal in short retention times (4 and 10 days) compared to conventional pond systems. Yet, a shallow depth operation involves reducing the total volume of the pond, but it requires a greater investment and increases operating costs because it requires a larger surface for a given effluent flow. Still, there is potential to increase microalgae biomass production and nutrient removal from wastewater while reducing capital costs. One way, highlighted in the literature, is the change of the operational depth of the algal pond, shifting the amount and frequency at which microalgae cells are exposed to optimal light [13], significantly increasing the biomass productivity for 400 mm deep HRAPs in 134–200% compared to 200 mm deep HRAPs. Thus, increasing the depth of the ponds could allow maintaining the quality of wastewater treatment and may reduce operating and capital costs. HRAP systems also appear to be more economically viable when combined with biofertilizer production rather than biogas [14].

The algal biomass can be used to produce carbon-neutral products, such as biofuel, feed, biofertilizer and bioplastic integrated with biorefinery, circular bioeconomy and the valorisation of organic waste biomass. Either selling the algal biomass as a product or co-using it to improve the biofuel, combining algal treatment with wastewater treatment would allow to lower the cost of WWTPs. The production of biofuel involves removing CO_2 and producing a high-purity CH_4 stream (bio methane) that can replace traditional natural gas [15,16]. Due to their benefits, biogas upgrade techniques for biomethane production are increasingly being explored at the industrial level [17,18] and several studies focus on making the process more accessible [19,20] and with less carbon released into the atmosphere.

Studies using LCA concluded that HRAPs can help in reducing environmental impacts and costs associated with wastewater treatment compared to conventional systems, especially in small communities [21–23], i.e., for less than 10.000 inhabitants. For example, Kohlheb et al. [24] used algal pond system construction and operation data for a benchmarking comparison with an activated sludge-based sequencing batch system (SBR) with comparable removal rates and similar inlet wastewater. They only focused on the actual wastewater treatment aspects of these technologies, excluding sludge treatment from this analysis, and based on a total life expectancy of 40 years. Therefore, it appears that using HRAPs instead of conventional wastewater treatment technologies can increase the sustainability and cost-effectiveness of wastewater treatment, especially if implemented in small communities, warm climate regions and associated with biofertilizer production.

The objective of this research is to discuss the technological and management aspects leading to greater energy savings in WWTPs. Based on data on energy costs collected from the literature, WWTPs' websites and SABI financial reports, a mixed methodology was used, which is one of the novelties of the work. The qualitative aspects consisted of a narrative analysis of the information about technologies, treated volumes and operating costs, while the quantitative approach involved calculating the specific energy consumption (kWh/m^3), energy operating costs (EUR/m^3) and energy operating costs per population equivalent (EUR/inhabitants). The energy cost of activated sludge-based technologies and HRAP technology from 11 Portuguese WWTPs and other international studies were compared. The most common biological processes for domestic or urban wastewater treatment in Portugal is activated sludge, followed by biological filters, stabilization ponds, anaerobic digestion (UASB) and constructed wetlands [25–27], which are operated by 45 companies. There are no HRAP processes operating in Portugal for wastewater treatment, and one of the other novelties of the work is to show the advantages of having such a system operating in the country. This study also calculated the energy cost savings by applying a savings ratio to the energy costs of activated sludge-based technologies calculated with data from previous literature.

2. Material and Methods

A mixed methodology, involving qualitative and quantitative aspects, for collecting and analysing data from wastewater treatment plants was used.

Data on activated sludge WWTPs' characteristics and their expenses and operational costs for 2020 were collected from online reports of 11 Portuguese management companies and the SABI database (https://login.bvdinfo.com/R0/sabineo accessed on 11 May 2022). The sample of WWTPs was scattered across the mainland: 3 in the north, 2 in the centre, 2 in Alentejo, 3 in Lisbon and 1 in Algarve. Data on HRAP systems and other activated sludge systems, as well as their operating costs, were collected from international studies for volumes of treated wastewater in the range of values found in the 11 Portuguese companies, as presented in Table 1 of the Results section.

Table 1. Specific energy consumption (SEC) for activated sludge and HRAP technologies.

Source	Technology	SEC (kWh/m^3)
Garfi et al. [21]	HRAP Activated sludge	0.25 1.26
Arashiro et al. [14]	HRAP + biogas production HRAP + biofertilizer production Activated sludge	0.06 0.08 0.89
Kohlheb et al. [24]	HRAP Activated sludge	0.17–0.25 0.45
Rego [28] 1)	Activated sludge	0.68–0.98
Moreno et al. [29] 1)	Activated sludge aeration with turbines Activated sludge aeration with air bubble	0.73 0.80
Turkmenler [30]	Activated sludge	0.38–0.43
Siatou et al. [31]	Activated sludge	0.90
This study 1)	Activated sludge	0.57

1) Portuguese studies.

Operation and maintenance (O&M) costs comprised labour, electricity, purchase of chemical products (i.e., consumables), sludge disposal and ordinary and extraordinary maintenance (e.g., equipment replacement). However, only the energy costs were analysed in this work. From the data on yearly or daily energy consumption (EC, kWh) and yearly or daily volumes of treated wastewater (V, m^3), the values of specific energy consumption per volume of treated wastewater (SEC, kWh/m^3) were computed through Equation (1). The specific energy operating cost (SEOC, EUR/m^3) was computed from the energy operating cost (EOC, EUR) and volume of the treated wastewater using Equation (2) and the specific energy operating cost per p.e. (EUR/inhabitants) from Equation (3).

$$\mathrm{SEC_i} = \frac{\sum_{i=1}^{n} \mathrm{EC_i}}{\sum_{i=1}^{n} \mathrm{V_i}} \tag{1}$$

where $\mathrm{SEC_i}$: specific energy consumption per volume of treated wastewater in system i (kWh/m^3); $\mathrm{EC_i}$: energy consumption in system i (kWh); and $\mathrm{V_i}$: volume of treated wastewater in system i (m^3).

$$\mathrm{SEOC_i} = \frac{\sum_{i=1}^{n} \mathrm{EOC_i}}{\sum_{i=1}^{n} \mathrm{V_i}} \tag{2}$$

where $\mathrm{SEOC_i}$: specific energy operating cost per volume of treated wastewater in system i (EUR/m^3); $\mathrm{EOC_i}$: energy operating cost in system i (EUR); and $\mathrm{V_i}$: volume of treated wastewater in system i (m^3).

$$\mathrm{SEOCP_i} = \frac{\sum_{i=1}^{n} \mathrm{EOC_i}}{\sum_{i=1}^{n} \mathrm{p.e._i}} \tag{3}$$

where $\mathrm{SEOCP_i}$: specific energy operating cost per p.e. in system i (EUR/inhabitants); $\mathrm{EOC_i}$: energy operating cost in system i (EUR); and $\mathrm{p.e._i}$: equivalent population in system i (inhabitants).

Results found for activated sludge in the 11 Portuguese WWTPs were compared with results found in the literature for similar WWTPs as well as for HRAPs.

Figure 1 shows the methodologic procedure followed in this study.

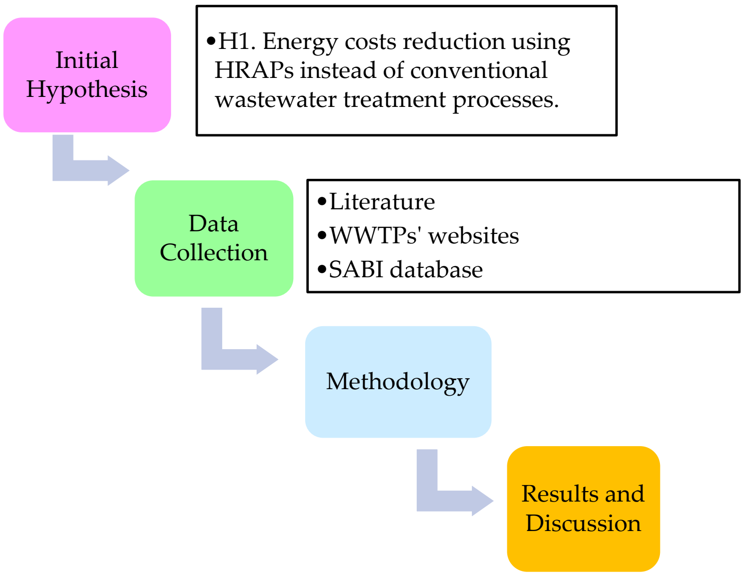

Figure 1. Schematic representation for the methodology.

3. Results and Discussion

The main operating costs of the 11 Portuguese WWTPs were wages and electricity, representing 48.32% and 48.43% of total costs (Figure 2), respectively, for treated wastewater flowrates ranging 8392–496,618 m^3/d and p.e. between 11,659 and 593,451 inhabitants. Gandiglio et al. [1] also found that electricity accounted for approximately 25–50% of operating costs. For populations between approximately 11.660 and 23.470 inhabitants, the personal costs were higher than the energy costs, reaching an equilibrium between these two costs for populations of approximately 57.170 inhabitants. However, for populations greater than 57.170 inhabitants, the results were inconsistent, as both higher values for electricity costs and higher values for personnel costs appeared with no correlation with population or volume growth. This inconsistency is related to the technologies used for wastewater treatment in the WWTPs of the 11 companies, with higher energy costs where more pumping equipment, turbines and compressors were used.

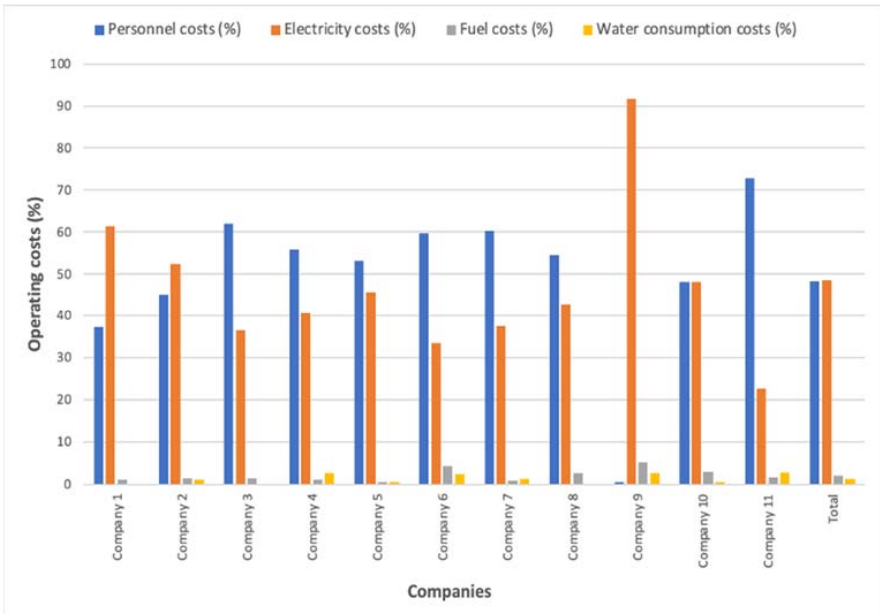

Figure 2. Operating costs for the 11 Portuguese wastewater management companies.

Nearly 11% of the treated wastewater was reused for no potable applications, namely, for garden watering, irrigation and washing floors and equipment. According to Longo et al. [32], aeration in activated sludge systems consumes 0.18–0.8 kWh/m^3 which represents 40% and 75% of the total energy consumed in large and small plants [33,34].

Approximately 7.3% of the energy produced by the Portuguese WWTPs was through, namely, biogas conversion with conventional technologies, which release carbon into the atmosphere. This suggests a great dependence on energy from external sources. The $SEOC_i$ values in the 11 Portuguese WWTPs ranged between 0.11 and 0.87 EUR/m^3 (0.28 EUR/m^3 on average), which corresponded, in terms or energy consumption, to SEC_i values of 0.33–0.83 Kwh/m^3 in 2020 (0.57 EUR/m^3) on average. The average SEOCP was 73.7 EUR/inhabitants. Kohlheb et al. [24] found SEOCs for activated sludge ranging 0.17–0.26 EUR/m^3 and 0.13–0.18 EUR/m^3 for HRAPs. Rego [28] reported an interval between 0.14 and 0.19 EUR/m^3 (activated sludge) for volumes ranging 2010–11,878 m^3/d.

Table 1 presents results on SEC_i for activated sludge and HRAPs found in international studies, as well as the values calculated for the 11 Portuguese WWTPs. Another two studies on Portuguese WWTPs using activated sludge systems were found. However, the values were reported for 2012 [28] and 2015 [29], respectively. Populations ranged from 11,342 to 64,414 p.e. [28] and from 2000 to > 50,000 inhabitants [29]. These values were in the same range as those in the present study. Only three studies were found for HRAP systems with energy consumption data [14,24]. The studies of Garfi et al. [21] and Arashiro et al. [14] considered p.e. < 10,000 inhabitants and a daily flowrate of 2000 m^3/d.

The results in Table 1 show that the average SEC for activated sludge in this study (0.57 kWh/m^3) was below the values found in other Portuguese studies (0.68–0.98 kWh/m^3) in 2012 [28] and 2015 [29], but within the range of values found in international studies (0.38–1.26 kWh/m^3).

This suggested the success of the managers of Portuguese WWTPs in reducing energy costs. Yet, there was no statistical correlation between SEC (kWh/m^3) and population size (p.e. in inhabitants) and between SEOC (EUR/m^3) and the volume of wastewater (m^3) for the 11 Portuguese WWTPs, which seems to indicate that the type of technology used, particularly if it was based on pumping systems, turbines or compressors, had more weight on energy consumption than the population served or the volume treated. Thus, measures to reduce costs and increase energy efficiency should, first, focus on these types of technologies.

In Figure 3, the lower correlation between the SEC and population for the 11 wastewater management companies in the years 2018, 2019 and 2020, whose variations were explained using equipment with different energy consumptions, can be seen.

HRAP systems displayed lower energy consumptions, ranging 0.06–0.25 kWh/m^3. Cardoso et al. [33], analysing energy consumption data from 19 countries, did not find a direct relationship between SECi values and the volume of treated wastewater. The load factor, dilution factor, age of the WWTP, location and technological performance could impact energy consumption more than the treated volume. Low load factors led to a low energy performance [35], and when it reached 100%, SECi decreased [35]. Longo et al. [32] observed low SECi values associated with very low dilution factors. Haslinger et al. [36] highlighted the impact of technology on energy consumption by concluding that WWTPs with aerobic sludge stabilization showed higher SECi values than the ones with mesophilic sludge digestion. Moreover, Turkmenler [30] argues that energy consumption depends on the concentration of pollutants in the incoming water.

To evaluate the decrease in SEC in recent years (2018 to 2020), the minimum, maximum and average energy costs by year were calculated for the 11 WWTPs using activated sludge data (Figure 4.).

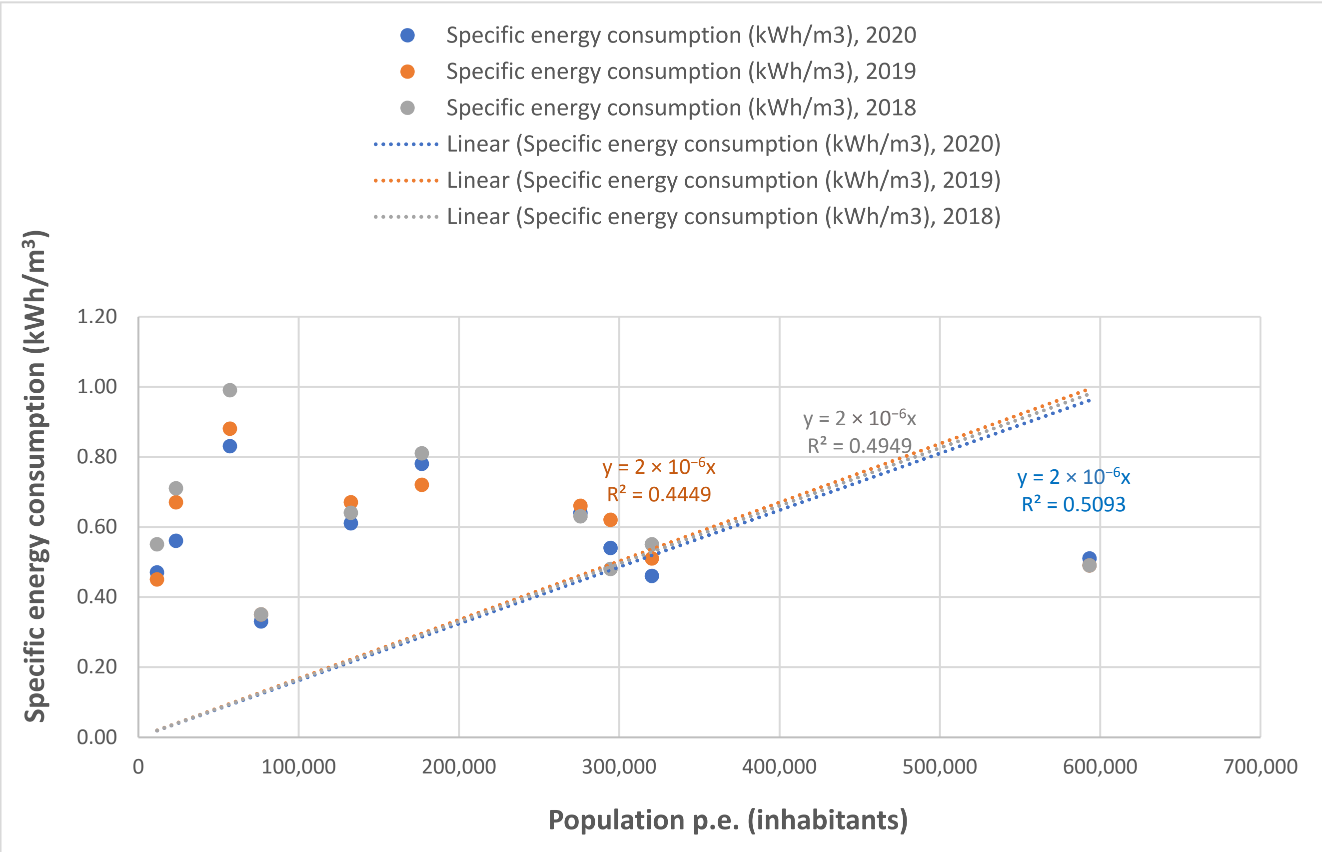

Figure 3. Linear (specific) energy consumption for the 11 Portuguese wastewater management companies.

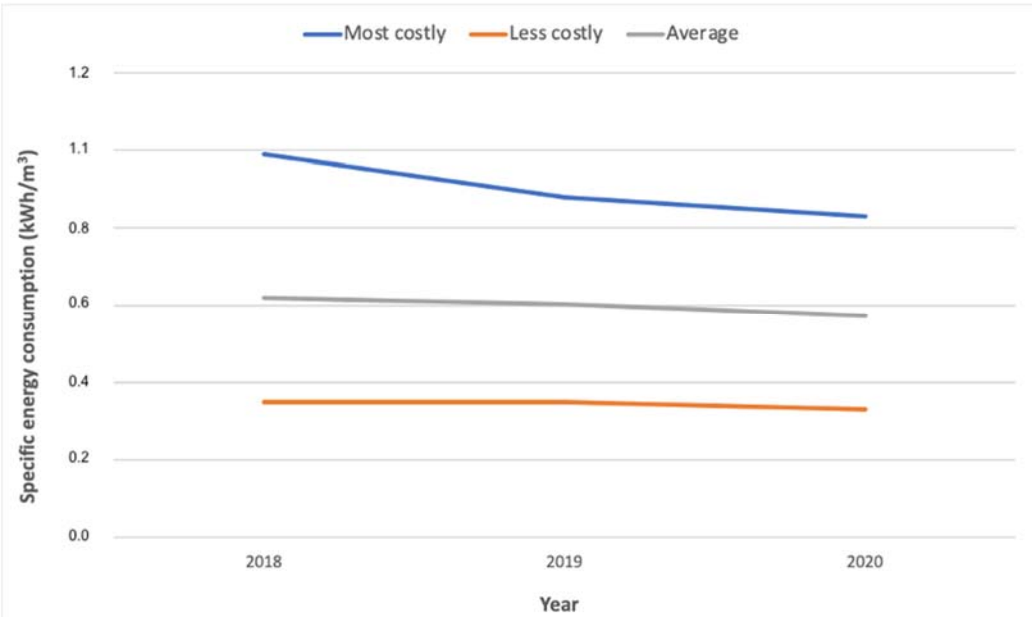

Figure 4. Evolution of the specific energy consumption, 2018–2020, for the 11 Portuguese wastewater management companies.

In recent years, the energy consumption decreased due to changes in O&M procedures, such as the optimization of power and operating times of pumps, turbines and compressors, the introduction of online monitoring systems connected to solar panels, the introduction of sludge anaerobic digestion with biogas production, in addition to energy production in the WWTP spaces with the introduction of solar panels and mini wind turbines. However, on average, it was higher than expected (0.62 kwh/m^3 in 2018, 0.60 kwh/m^3 in 2019 and 0.57 kwh/m^3 in 2020). In Portugal, the most used methods for energy production in WWTPs are the conversion of biogas produced in digesters for sludge treatment [19] in electricity and heat in combined heat and power (CHP) systems [37–40]. Still, the fact that the WWTPs needed to stop the production of energy from biogas in the cogeneration unit to start the biogas upgrade appeared to strongly impact the profitability of the project. Yet, this was expected, bearing in mind that electricity is much more expensive. Cornejo et al. [41] reported SEC for UASB with two maturation ponds with water reuse and energy recovery of approximately 1.51 kWh/m^3.

Besides energy, other relevant costs in the WWTPs were related to total investment, labour and O&M. However, the former could be partially covered by government incentives (e.g., investment subsidies). The other two costs (labour and O&M) are not easy to reduce, as they affect the daily operations of biomethane plants [39]. It seems clear that, under such constraints of the baseline scenario, profitability is yet to be achieved.

During recent decades, natural technologies (also known as nature-based technologies, such as constructed wetlands and algae-based systems) for wastewater treatment have gained interest as an attractive alternative to conventional treatment systems in small communities [7–9,42–44]. Natural treatment technologies use modified natural self-treatment processes that occur in soil, water and wetland environments, thus, requiring lower energy consumption, simplicity of operations and lower investments compared to conventional systems [44]. The specific area requirement for conventionally activated sludge, constructed wetlands and HRAPs is 0.6 m^2/inhabitants, 3.5 m^2/inhabitants and 6 m^2/inhabitants, respectively [14]. Constructed wetland systems appear to be more adequate when there is a land restriction, since they have a smaller footprint compared to HARPs (3.5 m^2/inhabitants vs. 6 m^2/inhabitants).

Kohlheb et al. [24] concluded that pond treatment technology is more energy-efficient than activated sludge-based SBR and requires only 22% of energy consumption. Furthermore, they concluded that HRAP systems are more economically advantageous (EUR0.18/m^3 for HRAP and 0.26EUR/m^3 for activated sludge-based SBR). Regarding SEC_i, values ranged from 0.04 to 0.10 kWh/m^3 (HRAP with "Low Energy Algae Raceway") and 0.45 kWh/m^3 (SBR). By contrast, activated sludge SBR systems require approximately 74% of the consumed energy for aeration. Lorenzo-Toja et al. [45] reported specific energy operating costs for the stabilization of ponds to be approximately 1 kWh/m^3.

The higher O&M costs in activated sludge and HRAP scenarios are mainly due to the higher energy consumption. Indeed, energy consumption is a major contributor to the O&M costs in WWTPs using activated sludge. Yet, it is currently difficult to economically outperform these technologies, as they can cost between 0.11 and 0.87 EUR/m^3 (0.28 EUR/m^3 on average). Garfi et al. [21] found an average SEOC of 0.79 EUR/m^3 (activated sludge), 0.40 EUR/m^3 (constructed wetlands) and 0.42 EUR/m^3 (HRAP), which gave $SEOC_{HRAP}/SEOC_{\text{activated sludge}}$ = 0.532. Applying this ratio to the range of $SEOC_i$ found in this study delivered a result of energy costs ranging 0.059–0.46 EUR/m^3 (0.15 EUR/m^3 on average) if HRAP was to be used in our sample of 11 WWTPs. In other words, the WWTPs would benefit from a cost reduction of 0.05-0.41EUR/m^3. Using p.e. values and the ratio found in Garfi et al.'s [21] work, SEOCPHRAP/SEOCP activated sludge equalled 0.303, and the hypothetical SEOCi for implementing HRAP systems in Portugal would cost between 6.7 and 78.8 EUR/inhabitants (22.4 EUR/inhabitants on average), i.e., a cost reduction between 15.4 and 180.8 EUR/inhabitants.

According to Kohlheb et al. [24], HRPA systems present environmental advantages, since the CO_2 sequestration with algal biomass is approximately 146.27 × 10^{-3} kg CO_2 equiv./m^3, whilst for activated sludge SBR systems, CO_2 sequestration is 458.27 × 10^{-3} kg CO_2 equiv./m^3. In fact, the environmental impacts of conventional effluent treatment methods (activated sludge scenario) are estimated to be 2–5 times greater than those of nature-based technologies (constructed wetlands and HRAP scenarios). This is mainly due to the high energy consumption and use of chemicals in WWTPs using activated sludge. Similar results were obtained from previous studies that compared the potential environmental impacts of activated sludge and constructed wetland systems [31,32,36]. As there are many WWTPs with several treatment technologies, along with many algae species (each with different treatment efficiencies), it was not possible to carry out a feasibility study for WWTPs using microalgae. Therefore, more specific details on WWTPs are needed, namely, for comparing algal growth. Another limitation of this research was the lack of a database with energy costs for each WWTP and for the effluent treatment technology used. As a result, the calculations need more refinement, and some were based on the methodology of Garfi et al. [21].

At a time when sustainability is on the agenda and water governance is a European and global issue, especially in Mediterranean countries where drought periods are longer, it is urgent to find solutions to face the scarcity of water. In the framework of the Sustainable Development Goals, wastewater management entities, although they may benefit from government subsidies, ideally should achieve profit while not compromising the achievement of social and environmental sustainability. Furthermore, in the current growing context of the circular economy, the CEBM is gaining increasing proselytes by providing management practices that are simultaneously sustainable at the economic and environmental levels. Thus, we are currently witnessing a paradigm shift in wastewater treatment for these types of companies. The highest operating costs were those with labour and energy, within this framework. Studies that allow for a reduction in energy costs are of particular importance. In fact, the current trend is to look for alternative water supply solutions that sometimes involve the reuse of wastewater [46].

4. Conclusions

According to the results obtained in this study, HRAP-based technologies might be a good technological alternative solution for wastewater treatment, especially for small communities. Besides their efficiency in removing pollutants, they can generate added-value products from algae biomass valorisation and can represent energy cost savings of 0.05–0.41 EUR/m^3, 15.4 EUR/inhabitants and 180.8 EUR/inhabitants. Furthermore, this technology, in addition to being financially advantageous, makes it possible to eliminate the carbon footprint by saving approximately 45 kg CO_2 eq/inhabitants a year, suggesting that biotechnology is starting to position itself as a mandatory future solution in the wastewater treatment sector. Due to energy costs not being dependent on wastewater volume but rather on factors such as the load, dilution, technology, infrastructure age and location, future research paths should include an economic analysis of full-scale systems using data obtained during long-term monitoring.

Author Contributions: Conceptualization, E.S. and H.E.; methodology, E.S., A.A. and I.L.; software, E.S., A.A. and I.L. validation, E.S., A.A. and I.L. formal analysis, E.S., A.A., I.L. and H.E., investigation, writing—original draft preparation, E.S., A.A. and I.L.; writing—review and editing, E.S., A.A., I.L., P.M. and H.E.; supervision, E.S.; project administration E.S.; funding acquisition, E.S., A.A., I.L., P.M. and H.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research is financed by National Funds of the FCT—Portuguese Foundation for Science and Technology within the project «UIDB/04928/2020» and, under the Scientific Employment Stimulus-Institutional Call CEECINST/00051/2018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Restrictions apply to the availability of data. Data was obtained from (SABI, at https://sabi.bvdinfo.com/ (accessed on 11 May 2022)).

Acknowledgments: This research was financed by national funds from the FCT—Portuguese Foundation for Science and Technology—within the project UIDB/04928/2020, and under the Scientific Employment Stimulus—Institutional Call CEECINST/00051/2018.

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

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