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Technical–Economic Feasibility of a New Method of Adsorbent Materials and Advanced Oxidation Techniques to Remove Emerging Pollutants in Treated Wastewater

Víctor Fabregat * and Juana María Pagán *

Department of Engineering and Innovation, Regenera Energy, C. Molina de Segura, 8, 30007 Murcia, Spain
* Correspondence: vfabregat@regeneraenergy.es (V.F.); jmpagan@regeneraenergy.es (J.M.P.); Tel.: +34-69-3367-275 (V.F.)

Abstract: The focus on emerging contaminants (ECs) in wastewater has intensified due to the considerable risks they present to human health and wildlife. This paper presents the results of the technical–economic assessment of the Clean Up solution, carried out in the framework of the project entitled "Validation of Adsorbent Materials and Advanced Oxidation Techniques to Remove Emerging Pollutants in Treated Wastewater". The viability of the Clean Up system is evaluated by being applied as an advanced treatment system for treated urban wastewater, that is, for the elimination of pathogens and emerging pollutants (EPs), while considering the established quality criteria by current regulations. In this sense, it is a technology that has been successfully validated at an experimental level, and that offers similar removal performance compared to that of the most efficient alternatives available on the market. The technical–economic assessment has been conducted through a systematic process. Initially, the estimation involved the calculation of treatment costs for the Clean Up system when applied at an industrial scale. Subsequently, the treatment costs were estimated for the most favorable technological alternative to the Clean Up system from a technical–economic standpoint, also applied at an industrial scale, within identical scenarios and conditions as those assumed for the Clean Up system. The final step involved a comprehensive comparison of treatment costs between both alternatives, implemented uniformly under analogous conditions and assumed similar performance across all cases.

Keywords: emerging contaminants; urban wastewater

Citation: Fabregat, V.; Pagán, J.M. Technical–Economic Feasibility of a New Method of Adsorbent Materials and Advanced Oxidation Techniques to Remove Emerging Pollutants in Treated Wastewater. *Water* **2024**, *16*, 814. https://doi.org/10.3390/w16060814

Academic Editors: Joaquin Melgarejo and Francisco De Borja Montaño Sanz

Received: 22 January 2024
Revised: 4 March 2024
Accepted: 6 March 2024
Published: 10 March 2024

1. Introduction

Integrated into the term "contaminants of emerging concern, CECs", the term "emerging pollutants, EPs" can include all active pharmacological compounds (PhACs), personal care products (PCPs), endocrine disruptors (EDCs), herbicides and pesticides, together with all their derived metabolization compounds [1]. According to the NORMAN network, there are more than 1000 of these substances that have been identified in the European aquatic environment [2,3]. One of the works that can be cited to reveal the extensive number of compounds that are included under the term of EPs in wastewater, is the one carried out by Comero et al. [4], where they analyzed the concentration of 156 organic compounds in the effluent of 90 European WWTPs. The results demonstrated the presence of 125 substances, in concentrations from ng/L to mg/L. The compounds with the highest mean concentrations were the artificial sweeteners acesulfame (2.5 mg/L) and sucralose (12.9 µg/L), benzotrols (221 µg/L), several flame retardants and pharmaceutical compounds such as carbamazepine (4669 ng/L), diclofenac (174 ng/L) and codeine (826 ng/L).

One of the main concerns associated with emerging pollutants is the poor performance in the removal of some of them by the technologies that are currently used in the treatment of urban wastewater [5]. This is because these facilities are designed to eliminate other conventional pollutants required by current regulations (Directive 91/271/EEC). Technologies

used in water reclamation have the same problem, as they are not designed for EP removal, but for achieving a certain degree of quality in the reclaimed water to be reused that fits the level of quality required for each intended use (urban, industrial, agriculture, etc.). In this case, the referring legislation is Regulation (EU) 202/741 and Real Decreto 1620/2007, in Spain. The inefficiency in the elimination of EPs of the urban wastewater treatment and water reclamation systems that have been used until now causes the presence of some of these pollutants in the aquatic environment and/or in the reclaimed waters used in irrigation. This can entail several consequences, both in relation to environmental terms and public health. In this sense, the following aspects should be highlighted [4,6–10]: (i) human toxicity and ecotoxicity, (ii) presence and persistence, (iii) absorption by crops and (iv) effect on crops.

There are many challenges related to non-regulated pollutants whose effects are not fully understood. For instance, there is a threat linked to antibiotic-resistant bacteria, whose living environments are domestic wastewaters. These bacteria and their genes are even present in the reclaimed wastewater [3,11,12]. Therefore, there is an evident urgency to control and remove the pollutants that allow these bacteria and genes to proliferate in the WWTPs. As commented, the presence of EPs in treated waters discharged into water bodies or in reclaimed waters used in agriculture may carry a risk to human health or the environment. This has fostered the development of specific regulations for their control of water resources. Firstly, reference should be made to Directive 2013/39/EU, regarding priority substances in the field of water policy. This modifies the Directive 2008/105/CE, mentioned above, and establishes the EQS, defined as Maximum Allowable Concentrations (MAC), for a total of 45 compounds classified as priority substances, priority dangerous substances or other pollutants, in continental surface waters. This list is extended using the Commission Implementing Decision (EU) 2018/840, which establishes a watch list of substances for union-wide monitoring in the field of water policy. On the other hand, the European Commission is promoting the reuse of wastewater and, in this way, it has just developed Regulation (EU) 2020/741 on minimum requirements for water reuse. This regulation defines the microbiological and physicochemical parameters that must be measured in reclaimed water, and their associated MAC and monitoring frequency. That regulation does not establish, for the moment, limits for EPs in reclaimed water. However, the surveillance of some EPs such as personal care products, pharmaceuticals, drugs, etc., in irrigation water, has been established with a view to defining these limits in the near future. Another aspect to highlight of this regulation is that it establishes a series of obligations for water reclaiming plant operators, in addition to complying with the quality required for reclaimed water. In particular, the establishment of a risk management plan for reclaimed water is mandatory, in consultation with relevant stakeholders, such as wastewater providers, or end users, to address potential additional hazards.

EPs can be considered organic compounds, with medium or low biodegradability for which, in general, the biological treatments of WWTPs are not effective. Currently, there is a large number of works focused on the removal of EPs [13,14], that is, the development of water treatment processes for reducing and even eliminating the presence of said pollutants in treated water, obtaining higher quality water in the effluent of WWTPs. The most relevant ones are (i) adsorption processes, (ii) membrane processes, (iii) advanced oxidation (AOPs) and a combination of systems among others [15,16]. Within AOP processes, the most common use is combinations of ozone, hydrogen peroxide and UV radiation, with or without the use of catalysts [17,18].

The results of the different works carried out in recent years on the elimination of EPs in WWTPs have concluded, almost in a generalized way, that the most efficient technologies, both from a technical and economic point of view, are ozonation [19,20] and Powdered activated carbon (PAC) [21,22], both applied in WWTPs that already have advanced treatments for suspended solids and nutrients removal. These treatments must also include a final filtration stage, after O_3/PAC stage. That last stage would be a gravity sand filter, including biofilm formation, in the case of the O_3. In the case of PAC, they could be used as

sand filters, microscreens, cloth filters or even membranes of microfiltration/ultrafiltration (MF/UF). Both processes are already being implemented at an industrial scale in WWTPs to avoid the incoming of emerging compounds into water bodies. In general, they offer similar EP removal performance (around 80%) at very similar costs (somewhat higher in the case of PAC treatment).

In this scenario, the Clean Up Project [23] aims to develop and validate a technology for the removal of EPs that presents as an alternative on a technical and economic level to the aforementioned treatments [24–28]. The EPs and pathogens contained in the treated wastewater have become a very important issue to consider in order to maintain the quality of the waterbodies and also reuse water without people, animals and ecosystems facing any risk. However, its removal is not guaranteed in the current WWTPs when conventional treatments are applied. This is because conventional secondary (e.g., activated sludge process) and tertiary such as nutrient removal, filtration and disinfection treatments in WWTPs are not effective in the removal of most EPs entering WWTPs [29]. A wide range of advanced treatment methods have been investigated for the removal of EPs from wastewater, including consolidated (activated carbon adsorption, ozonation and membrane filtration) and not intensively implemented treatments, such as advanced oxidation processes. The technologies that have been shown to be the most effective are oxidation (ozonation, particularly) and adsorption (PAC, particularly). Meanwhile, membranes have the inherent problem of the concentrate stream, which is why they cannot compete with the previously indicated methods. The Clean Up solution is based on the combination of these two technologies (adsorption and oxidation), but with an innovative approach that enables obtaining a treatment that can compete in efficiency with the aforementioned technologies. In previous research works, the Clean Up solution technology is described in detail [30–35]. This research proceeds to conduct the technical–economic feasibility study of the Clean Up technology.

In summary, the Clean Up process is designed to treat the effluent from WWTPs, removing pathogens and EPs, among other compounds, in the EPs case, with yields higher than 80%. The treated water can thus be discharged into water bodies without risk, or be used in agriculture, since a priori it would comply with the quality levels defined by the related regulation. Although the main stages of treatment for the removal of EPs are adsorption and oxidation, the treatment includes additional stages, whose mission is to ensure the correct functioning of the main stages. The stages that make up the Clean Up System and its operation are described below. (i) Ultrafiltration (UF), first of all, the effluent coming from the WWTP is pre-treated to remove the suspended solids and colloids that it could still contain, reducing that way its turbidity, *as* those compounds can negatively affect the following treatment stages. The selected technology is ultrafiltration due to the high quality of the produced permeate and its compactness. (ii) Adsorption (Ad), the permeate of the UF, with a flow rate of 5 m^3/h, goes then to the adsorption stage, where it passes through a column filled with the adsorbent material in an upward flow and fluidized bed regime, and then the EPs retained in the material. The adsorbent material is a non-soluble polymer of β-cyclodextrins (βCDs) cross-linked with DABCO (1,4-Diazabicyclo [2.2.2] octane) and BDE (1,4 butanediol diglycidyl ether). This material has been selected based on extensive laboratory tests in which the adsorbent potential of different types of CDs, native or modified, has been evaluated with a series of EPs, whose presence in treated wastewater was previously verified. (iii) Photocatalysis (Ph), the effluent from the adsorption stage may still contain residual amounts of organic pollutants or EPs with low adsorption rates due to the selectivity of the material. For that reason, the treatment includes a final stage of photocatalysis for oxidizing these compounds, so that the removal performance of the adsorption–photocatalysis system reaches at least 80% for the EPs. In the present project, this technique uses TiO_2 as a catalyst since it is non-toxic, low cost, and has high chemical stability and superior photoelectronic properties [36]. (iv) Desorption (Ds), like any adsorbent, CDs have a maximum adsorption capacity, so that when this is reached, the EPs pass through the column without being retained. At that time, the column

is regenerated by passing a desorbing agent (NaCl solution) that drags the adsorbed EPs out of it, producing a concentrate of EPs that must be subsequently treated. In this way, the column is ready to be used in a new adsorption cycle. Based on laboratory tests carried out, it has been determined that the NaCl solution meets the requirements of a desorbing agent for this application. (v) Pulsed light (PL), the concentrate of EPs in NaCl solution produced in the desorption stage is then treated in an advanced oxidation process, looking for the Eps' destruction using direct photo-oxidation. This technique uses huge spectrum light pulses at high intensity, short duration and high frequency, producing a high-power light with a moderate consumption of electrical energy. The possibility of adding H_2O_2 to promote the production of OH· radicals and increase the performance of removing refractory compounds is also considered.

Figure 1 shows the process flow chart. The effluent from the WWTP containing EPs is firstly treated by UF in order to remove those components that can unnecessarily exhaust the adsorbent (β-CD) in the column. Microbiological parameters (*E. coli*, *C. perfringens* and *C. perfringen* spores) are removed in the pre-treatment step by the ceramic ultrafiltration membrane (0.4 μm), and for the following sampling points the values are maintained at <10 cfu/100 mL. In any case, and given that photocatalysis has a disinfection capacity, wastewater disinfection is enhanced by this last treatment step. The permeate passes then to the adsorption, the second stage, through the fluidized bed of cyclodextrin's polymer, where most of the EPs are retained. After that, the water is treated by photocatalysis with TiO_2 for the removal of the remainder of EPs (third stage). The desorption process consists of making a NaCl solution pass through the bed of exhausted cyclodextrins. That solution drags the EPs from the polymer producing a concentrate which is afterwards treated by another advanced oxidation technique: pulsed light.

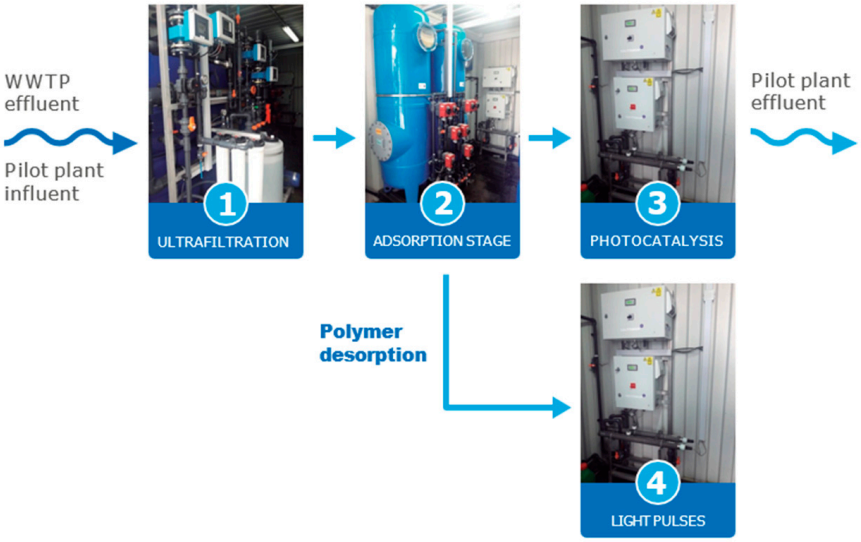


Figure 1. Experimental scheme of the modular pilot plant.

In addition, it is important to mention that the energy required by the Clean Up system is supplied by photovoltaic panels, covering the whole energy demand of the solution, as explained in Section 2.2. Therefore, the project Life Clean Up aims not only to use innovative processes in order to remove a wide range of EPs from urban wastewater at an industrial scale, but is also expected to be energy self-sufficient by implementing a solar panel system.

2. Methodology and Calculation of Treatment Costs

2.1. Application Scenarios for Clean Up Technology

When implementing the treatment system described in the previous point at an industrial scale, the primary application scenario to consider is the treatment of WWTP

effluents for removing EPs and pathogens. The technology could be applied both to produce an effluent that could be discharged into water bodies and to produce reclaimed water that could be used in agriculture. Although there is no legal reference to the maximum allowable concentration of EPs, neither in the water that is discharged into water bodies nor in the reclaimed water used in agriculture, in both cases an effluent containing less than 20% of the initial concentration of EPs would be obtained. The application of this technology in these two scenarios could be carried out both in current and new WWTP projects. The two application cases are described in more detail below.

Urban wastewater treatment: the solution would be applied in WWTPs that discharge treated water into water bodies, as almost all facilities in Europe do. In addition, these WWTPs may or may not already have advanced treatments for nutrients and suspended solids removal, which divides this scenario into two possible sub-scenarios. In any case, the conventional technologies used in WWTPs have not allowed us to successfully remove EPs yet. This, along with the concern due to the increasing presence of EPs in the water cycle, has led to the development of various technological alternatives for the treatment of these wastewaters, some of them in the industrial implementation phase. These alternatives are basically ozonation and PAC, in which both cases are combined with the filtration stages, with which it is possible to achieve EP removal efficiencies above 80%. Obviously, the application of these treatments supposes an increase in the cost of wastewater treatment, which in this case is around 30%. The Clean Up process is presented as an alternative solution to those mentioned above, by allowing higher than 80% EPs removal, logically together with an increase in the cost of wastewater treatment. As this removal yield is similar to those of the alternatives mentioned above, it would be necessary to develop a competitive process in terms of treatment costs. In order to properly compare the costs of the different technologies, these costs should be obtained in all cases for the same EP removal performance. This is the assumption that is adopted in the present technical–economic study.

Urban wastewater reclamation. In this case, the Clean Up solution would be applied in WWTPs to produce reclaimed water from secondary effluent, suitable to be reused in agriculture, according to the current regulation (Regulation (EU) 2020/741). This case is especially relevant in water-stressed regions, such as the Mediterranean Basin. As in the previous case, two sub-scenarios would emerge depending on whether the WWTP already has or not an advanced treatment for nutrients and suspended solids removal. It has to be pointed out that the Clean Up system, besides the EPs removal, will act as advanced or tertiary treatment, removing BOD, suspended solids and pathogens, providing water suitable for irrigation. In this case, the situation is the same that was found in the previous case: water reclamation technologies commonly used are not efficient against EPs, except nanofiltration (NF) and reverse osmosis (RO). In any case, these membrane technologies are only used when the water has a high salinity, as they are the only viable alternative, but not with the aim to remove EPs, since in this case, these compounds would only be concentrated in a waste stream, which should be finally treated with a destructive technique. The technologies that have been defined as suitable in the previous point could also be suitable for reclaiming wastewater. That would be possible by implementing a final stage of UV disinfection, as the water produced by the filtration stages carried out after the O_3/PAC treatment would have very low values of particles and organic matter, but could also have a residual microbiological charge. Due to the low turbidity of the filtered water, the proper disinfection technology would consist of a UV irradiation and a final maintenance chlorination. This is the treatment scheme assumed in the present technical–economic study, as the alternative to the Clean Up system in water reclamation. The Clean Up solution would be suitable for water reclamation, as said before, without any additional stage. Anyway, in this case, it would be also necessary to implement the final chlorination step, and that has been assumed in the current study. On the other hand, it could also be considered the substitution of the UF stage of the Clean Up system by other advanced, less expensive treatments for suspended solids removal, such as direct filtration through

sand, microscreens, textile filters, etc. Assuming similar performance for all the technical alternatives, the Clean Up solution will be advantageous if the cost of water reclamation that it entails is lower than that of the contemplated alternatives. In water reclamation, the economic comparison of the Clean Up system with the alternatives O_3/PAC would be more advantageous for Clean Up than in the previous scenario (wastewater treatment for discharge) because the Clean Up solution would be suitable for producing reclaimed water, while the alternatives should be modified for including a final stage of UV disinfection. On the other hand, the increase in the wastewater treatment costs, in the water reclamation scenario, would not be held by the beneficiaries of the sanitation and water treatment service, as it is in the first scenario, but by the end users of the reclaimed water, who are usually farmers. In this sense, the current cost of reclaimed water for agricultural use can be a reference to assess the economic viability of the removal of EPs, in the context of water reclamation.

Along with the urban wastewater treatment/reclamation, there could be another scenario considered, in which the system would be applied for the treatment of industrial wastewaters containing refractory or toxic organic compounds, such as effluents from the pharmaceutical industry, for example. This study does not consider that potential application.

2.2. Energy Production by Photovoltaic Panels

Among the characteristics of the Clean Up system, the generation of electricity on site, using photovoltaic panels, in order to power the treatment plant, is highlighted. This is intended to reduce the operating costs of said treatment system, since, currently, the costs of setting up a photovoltaic plant and producing electricity with it, which is defined as LCOE (levelized cost of electricity), can be, under certain conditions, lower than the cost of consuming the electricity from the grid. For this reason, in the industrial implementation of the considered treatment system, the inclusion of a photovoltaic plant is also considered as an option, so that the cost of treatment including this option can be calculated. To determine a priori if the inclusion of the photovoltaic (PV) system is economically efficient, the LCOE is determined as a function of the capacity of the PV plant, which will depend on the treatment capacity of the plant with Clean Up technology, and for a specific geographical location, since that last aspect will determine the energy production capacity as a function of the m^2 of installed panels.

Information sources from IRENA (International Renewable Energy Agency) [37] and the application of the JRC Photovoltaic Information System (PVGIS) of the European Commission have been used in order to specify the parameters that are considered for calculating the LCOE in two locations and based on the installed power of the PV plant. The results of the costs calculated using these sources have been checked with our own information coming from real PV plants. Table 1 shows the information used as input in the application PVGIS. It has been supposed to be an installed peak PV power of 1 kWp, in order to later extrapolate the results to the desired PV plant power.

Table 1. Input data used in PVGIS application for calculating the energy production based on the installed PV power.

Locations	Murcia	Bari
Latitude/longitude	37.995, −1.170	41.121, 16.860
Solar radiation database	PVGIS-SARAH	
PV technology	Crystalline silicon	
Installed peak PV power, kWp	1	
System loss, %	14	
Mounting	Fixed	
Position	Free standing	
Azimuth	0°	
Slope	35°	

Table 2 shows the results obtained using PVGIS for the two considered locations and the calculated average.

Table 2. Performance of the PV system (1 kWp) obtained for the two considered locations and calculated average.

Location	Murcia	Bari	Average
Yearly PV energy production, kWh	1635	1480	1558
Yearly in-plane irradiation, kWh/m^2	2099	1895	1997
Year-to-year variability, kWh	45	58	52
Total loss, %	−22.1	−21.9	−22.0

For the cost calculation, the following considerations are used: (i) operational specific costs—40,000 EUR per installed MW and year; (ii) investment specific costs—in this case, cost varies based on the installed PV power (this variation is reflected in Table 3); and (iii) investment financing conditions—investment lifetime of 25 years, and a financing interest of 7% is fixed.

Table 3. Specific investment costs as a function of the installed peak PV power.

Installed peak PV power, kWp	100	1000	10,000	100,000
Specific investment cost, EUR/kWp	1500	1000	750	700

The results of the LCOE calculation in the indicated location and depending on the installed peak PV power are presented in Table 4.

Table 4. Costs of the PV facility based on the installed peak PV power.

Installed peak PV power, kWp	100	1000	10,000	100,000
Yearly PV energy production, kWh	155,750	1,557,500	15,575,000	155,750,000
Operational costs, EUR/year	4000	40,000	400,000	4,000,000
Operational costs, EUR/kWh	0.03			
Investment, EUR	150,000	1,000,000	7,500,000	70,000,000
Repayment fee	0.086			
Capital costs, EUR/year	12,872	85,811	643,579	6,006,736
Capital costs, EUR/kWh	0.08	0.06	0.04	0.04
Total costs (LCOE), EUR/kWh	0.11	0.08	0.07	0.06

Only in the cases where the PV power to install entails a LCOE lower than the considered price of consumed electricity from the grid (0.12 EUR/kWh), a PV plant installation, associated with a water treatment plant, is considered for cost calculation. In addition, it must be considered that in these cases, the consumed electricity will not completely come from PV panels. Alternatively, it could come from the grid, depending on the time of the day. Therefore, the criterion followed to size the PV plant is that it is able to supply all the energy that the treatment plant needs in the month of maximum PV production is maximum, which in this case is July. In this month, during daylight there will be an energy surplus, that is, energy not consumed by the treatment plant, which will be supplied to the grid. That energy will be similar to the energy consumed at night, so the energy balance will be null. However, the energy supplied to the grid and the one consumed by the treatment plant will not mean a null economic balance, as the assumed price of grid electricity (0.12 EUR/kWh) will be higher than the benefit obtained when supplying energy, similar to the estimated LCOE. During the rest of the months, the energy consumption of the treatment plant will be higher than the energy produced by the PV plant. In that

case, it is assumed that all the consumed energy will be taken from the grid, and all the produced energy will be supplied to the grid at a price similar to LCOE. This assumption does not exactly reflect the reality, as part of the electricity consumed by the treatment plant proceeds from the PV panels, and another part proceeds from the grid. In any case, this assumption has been reached because it facilitates calculations and because the difference with respect to calculating it as indicated is negligible, as it has been verified in an exploratory calculation carried out.

2.3. Technical Performance Evaluation

Previously, the treatment scheme of the Clean Up solution has been described at a basic level, as well as the forecasted application for this solution, once commercially developed. This section describes the issues related to the industrial implementation in a WWTP of the mentioned process, and particularly, the operational conditions, consumptions and performances that could be expected from said system are defined. This information is necessary for estimating the treatment costs of the considered technology and comparing it with the costs of the technical existing alternatives in the forecasted application scenarios. To estimate the performance of the Clean Up system at an industrial scale, the application scenarios have been considered: application in WWTPs that have an advanced treatment or not, and that aim to discharge treated water into water bodies or reclaim it to be used in agriculture. In addition, a treatment capacity between 1000 and 100,000 m^3/d has been considered. Due to the limitation of the Clean Up system's treatment capacity to 1000 m^3/d, as obtained in previous studies [35], a linear trend has been considered for the following orders of magnitude (10 units and 100 units of Life Clean Up in parallel).

The treatment system whose performance is intended to be calculated will have particular results, depending on the previously said application scenarios and, therefore, also particular costs. Regarding the calculation parameters used for sizing these systems, the operational conditions, consumptions and performances that could be expected from each considered system are defined below. For setting up these data, the values of 1000 m^3 for Case A are those obtained experimentally in the pilot plant. To conduct a more comprehensive study, not limited solely to the characteristics of the WWTP where the pilot plant has been located, other scenarios (Cases B, C, D, A' and B') have been considered. To facilitate a detailed analysis, the data required for these scenarios, which could not be obtained from the pilot plant, have been supplemented with bibliographic data [17–31,38–52].

Case A. The system is applied in a WWTP that does not have any advanced treatment for removing suspended solids after its secondary settlers, and where the treated water is discharged into a water body. The objective in this case is to limit the presence of EPs in the mentioned water body. The treatment system is composed then by all the elements included in the pilot plant; that is, a first stage of microfiltration followed by ultrafiltration for removing the suspended and colloidal solids, followed by the adsorption with cyclodextrins stage for EPs removal, and a final stage of photocatalysis for the degradation of the remaining organic pollutants. Below, the manner in which the implementation at the industrial level of the different stages that compose this treatment would be carried out, and the considerations that have been completed for estimating the treatment costs of the mentioned system are defined.

Direct filtration and ultrafiltration stage. The pilot plant includes a UF system with ceramic membranes, preceded by cartridge filtration (MF). This combined treatment is used to limit the amount of undissolved solids that reach the adsorption stage. If these solids were not removed by membranes, they could be retained or adsorbed on the adsorbent material, reducing the EP adsorption capacity and/or increasing the need for cleaning or regeneration operations of the adsorbent bed. To implement this system in a WWTP, the MF stage would be carried out by a direct filtration system using microscreens or cloth filters, technologies with filtration grades among 10–40 μm, which are well known and used in tertiary treatments in WWTPs. After that, the UF would be carried out, but in this case, using polymeric hollow-fiber membranes, instead of ceramic tubular membranes, as

the former are cheaper than the latter, and very well known and validated in advanced treatments in WWTPs. This is the system proposed for the implementation of the technology in a WWTP and the calculation of costs. In the case of the MF a direct filtration system calculated as an average of microscreens and cloth filters used in tertiary treatment is assumed. Then, the considered calculation parameters are the following: (i) TSS in secondary effluent—15 mg/L; (ii) recovery—98%. The remaining 2% of water is used in cleaning operations and is then led to the inlet of the WWTP, as its total suspended solids (TSS) concentration is similar to that of the WWTP influent (checked in results chapter): (iii) TSS removal performance—60%; and (iv) electrical consumption—0.007 kWh/m^3. In the case of the UF, a system with polymeric hollow fiber membranes would be adopted, operating in dead-end mode. Hydraulic and chemical cleanings are carried out using permeate, so a permeate tank sized for storing enough amount of water to achieve these operations is necessary. The considered calculation parameters for UF are the following: (i) recovery—85%. The retentate stream, produced in membrane cleaning, is directed to the inlet of the WWTP: (ii) TSS removal performance—98% and (iii) electrical consumption—0.25 kWh/m^3. Both in the case of MF and UF, the concentrated streams produced in cleaning operations are directed to the inlet of the WWTP. For this reason, the MF stage is sized considering the increase in the treatment capacity that these two recirculated volumes suppose, and for the UF, the followed procedure is similar, but considering only the concentrate stream generated in said operation.

Adsorption—desorption stage. In the pilot plant, the adsorption operation is carried out by passing the UF permeate through a column filter with an upward flow direction. Within this column is the adsorbent material, which is fluidized when the permeate passes through. The used adsorbent is β-CDs cross-linked with DABCO and BDE. Once the adsorbent is exhausted, the same can be regenerated by passing through the column a regenerant solution. The regenerant passes also in an upward flow and fluidizes the adsorbent, carrying away the previously adsorbed compounds, leaving the column free to be used again in a new adsorption cycle. The NaCl solution is subsequently treated using a pulsed light system to eliminate dragged compounds. This treatment will be described later. The pilot plant has two adsorption columns, so that continuous operation can be ensured, as one is always in operation, and the other one is in the regeneration or waiting phase. Finally, it must be said that the regeneration of CDs cannot be completed indefinitely, since CDs, just like any adsorbent, reduce their adsorption performance as regeneration cycles are added, so there comes a time when it is necessary to replace them. After the industrial implementation of the adsorption—desorption stage, the operation of that process in a WWTP would be similar to that of the one described above for the pilot plant. The design of the operation is carried out based on the results obtained through the design and operation of the pilot plant, except where specified. Next, the data used in the sizing of the adsorption process are shown. (i) EPs average concentration in UF effluent: 4.79 μg/L. It is the sum of the concentration of all the different EPs measured in this stream and averaged along a complete adsorption cycle; that is, until the exhaustion of the CDs: (ii) EPs average concentration in adsorption stage effluent—3.44 μg/L; (iii) amount of CDs as a function of the water flow to treat—9.5 kg/m^3/d; (iv) adsorption performance of CDs—4.24 m^3/kg CDs; (v) number of regeneration cycles until replacement of the CDs—10 cycles; (vi) electrical consumption in adsorption step—0.06 kWh/m^3; (vii) volume of regenerant solution as a function of the used amount of CDs—0.75 L/kg CDs; (viii) averaged value between 0.5 and 1 l/kg; (ix) it is assumed that when the CDs have to be replaced, the regenerant solution is also replaced; and (x) electrical consumption in desorption step: 0.04 kWh/m^3.

Photocatalysis stage. The pilot plant includes two photocatalysis (PH) reactors. The technology of the used reactors consists basically of monobloc vessels made of TiO_2, which include UV lamps, arranged parallel to the longitudinal axis of the vessel. Depending on the section of the vessel, one or more UV lamps are installed. In the case of the pilot plant, each vessel includes one lamp of 105 W, and the two PH reactors can be operated in series or parallel, since the contact time does not change. For the industrial implementation, the

process would be similar to the one carried out in a pilot plant but working with higher capacity reactors and/or with several reactors in parallel, since this is a modular technology with commercially available units with treatment capacity from 1 to 1000 m^3/h. The design of the operation is carried out based on the results obtained in the design and operation of the pilot plant. Next, the data used in the sizing of the photocatalysis are showed: (i) EPs average concentration in adsorption stage effluent—3.44 μg/L; (ii) EPs average concentration in PH stage effluent—0.90 μg/L; and (iii) electrical consumption—1.7 kWh/m^3.

Pulsed light stage. In the pilot plant, after each regeneration step, the regenerant volume is treated by an advanced oxidation process based on irradiating with pulsed light (PL). The pulsed light system uses a xenon lamp which generates light flashes with a polychromatic emission spectrum. The volume contained in the regenerant tank is continuously circulated to the pulsed light treatment device, which is adapted to work in continuous mode, and returned to the tank, until the contact time is high enough to ensure the removal of the concentrated EPs, leaving the regenerant available for the next desorption cycle. Regarding industrial implementation, a pulsed light system for continuous treatment mode must be developed or found, since what is present in the pilot plant is an adaptation of a discontinuous treatment system, for this purpose. The design of the operation is based on the results obtained through the design and operation of the pilot plant. Next, data used in the sizing of the pulsed light system are shown: (i) EPs removal rate—0.25 mg EPs/(l·h); (ii) information about the installed equipment of pulsed light—lamp with the power of 3000 W, 500 J of energy per pulse and 3 Hz of pulse frequency; and (iii) applied power—1 $kW/m^3/h$. The value taken from the design of the pilot plant, which has a lamp of 3 kW of power, was installed in a plant with a treatment capacity of 3 m^3/h. Table 5 includes the results obtained for Case A.

Table 5. Results obtained in Case A sizing.

WWTP Influent, m^3/d	1000	10,000	100,000
Direct filtration stage			
Filtration influent, m^3/d	1200	12,005	120,048
Filtration effluent, m^3/d	1176	11,765	117,647
TSS in filtration effluent, mg/L		6.1	
Wastewater flow (from filter cleaning), m^3/d	24	240	2401
TSS in wastewater from filter cleaning, mg/L		450	
Electrical consumption, kWh/d	8	84	840
Ultrafiltration stage			
Ultrafiltration influent, m^3/d	1176	11,765	117,647
TSS in ultrafiltration influent, mg/L		6.1	
Ultrafiltration effluent, m^3/d	1000	10,000	100,000
Wastewater flow (from membranes cleaning), m^3/d	176	1765	17,647
TSS in wastewater from membrane cleaning, mg/L		40	
Electrical consumption, kWh/d	294	2941	29,412
CDs adsorption stage			
CDs adsorption influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		28	
Required amount of CDs, ton	9.5	95	950
Volume of water treated per adsorption cycle, m^3	40,280	402,800	4,028,000
Time to complete 1 adsorption cycle, d		40	
Time until replacement of exhausted CDs, d		403	

Table 5. *Cont.*

Amount of adsorbed EPs until the replacement of exhausted CDs, kg	0.54	5.4	54.4
Equivalent CDs dose, mg/L		24	
Equivalent CDs consumption, kg/d	24	236	2358
Maximum adsorption capacity of EPs, mgEPs/gCDs		0.0057	
Electrical consumption, kWh/d	60	600	6000
WWTP influent, m^3/d	1000	10,000	100,000
Photocatalysis stage			
Photocatalysis influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		74	
EPs removal performance (CDs + PH), %		81	
Electrical consumption, kWh/d	1700	17,000	170,000
CDs regeneration stage			
Required amount of regenerant solution, m^3	7.1	71	713
Equivalent consumption of regenerant solution, L/d	18	177	1769
Equivalent electrical consumption, kWh/d	0.001	0.007	0.071
Pulsed light stage			
Regenerant to treat per adsorption cycle, m^3	7.1	71.3	713
EPs concentration in regenerant solution to recover, mg/L		8.0	
EPs to remove in PL system per adsorption cycle, kg EPs	0.05	0.5	5.4
Rate of EPs removal, g EPs/h	1.8	17.8	178.1
Required time for regenerating the solution in PL, d		1.3	
Installed PL power, kW	42	417	4167
Equivalent electrical consumption, kWh/d	16	158	1579
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year	759	7586	75,858
Installed peak PV power, kWp	389	3893	38,929
Production cost (LCOE), EUR/kWh	0.093	0.077	0.063
PV plant installation (YES/NO)	YES	YES	YES
PV plant production, MWh/year	606	6063	60,632
Net cost of consumed electricity (averaged), EUR/kWh	0.108	0.101	0.095

Case B. The system is applied in a WWTP which does not have any advanced treatment for removing suspended solids after its secondary treatment, and where the aim is to reclaim water for being used in agriculture, including the removal of EPs in the water reclamation process. As said, the Clean Up system can produce reclaimed water suitable for irrigation, with the only inclusion of a final step, after disinfection, with the aim to maintain a minimum residual oxidant in the reclaimed water. So, the treatment system is similar to Case A, but includes that final chlorination step (NaClO dosing) to maintain this minimum residual. The calculation parameters used are similar to the previous case, and the final disinfection stage is described below.

Chlorination stage. Composed of chlorination by NaClO dosing in a contact reactor. It should not be forgotten that disinfection is achieved by the previous photocatalysis stage and that chlorination is carried out to maintain an oxidizing residual downstream of the WWTP. The objective is to reach the quality parameters set up by the current regulation

(Regulation (EU) 2020/741) regarding the presence of pathogens in reclaimed water. The calculation parameters used are the following: (i) NaClO dose—3 gCl_2/m^3. Table 6 includes the results obtained for Case B.

Table 6. Results obtained in Case B sizing.

WWTP Influent, m^3/d	1000	10,000	100,000
Direct filtration stage			
Filtration influent, m^3/d	1200	12,005	120,048
Filtration effluent, m^3/d		1176	
TSS in filtration effluent, mg/L		6.1	
Wastewater flow (from filter cleaning), m^3/d	24	240	2401
TSS in wastewater from filter cleaning, mg/L		450	
Electrical consumption, kWh/d	8	84	840
Ultrafiltration stage			
Ultrafiltration influent, m^3/d	1176	11,765	117,647
TSS in ultrafiltration influent, mg/L		6.1	
Ultrafiltration effluent, m^3/d	1000	10,000	100,000
Wastewater flow (from membranes cleaning), m^3/d	176	1765	17,647
TSS in wastewater from membrane cleaning, mg/L		40	
Electrical consumption, kWh/d	294	2941	29,412
CDs adsorption stage			
CDs adsorption influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		28	
Required amount of CDs, ton	9.5	95	950
Volume of water treated per adsorption cycle, m^3	40,280	402,800	4,028,000
Time to complete 1 adsorption cycle, d		40	
Time until replacement of exhausted CDs, d		403	
Amount of adsorbed EPs until the replacement of exhausted CDs, kg	0.54	5.4	54.4
Equivalent CDs dose, mg/L		24	
Equivalent CDs consumption, kg/d	24	236	2358
Maximum adsorption capacity of EPs, mgEPs/gCDs		0.0057	
Electrical consumption, kWh/d	60	600	6000
Photocatalysis stage			
Photocatalysis influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		74	
EPs removal performance (CDs + PH), %		81	
Electrical consumption, kWh/d	1700	17,000	170,000
Chlorination stage			
Disinfection influent, m^3/d	1000	10,000	100,000
NaClO consumption (50% solution), kg/d	13	126	1261
CDs regeneration stage			
Required amount of regenerant solution, m^3	7.1	71	713

Table 6. *Cont.*

Equivalent consumption of regenerant solution, L/d	18	177	1769
Equivalent electrical consumption, kWh/d	0.001	0.007	0.071
WWTP influent, m^3/d	1000	10,000	100,000
Pulsed light stage			
Regenerant to treat per adsorption cycle, m^3	7.1	71.3	713
EPs concentration in regenerant solution to recover, mg/L		8.0	
EPs to remove in PL system per adsorption cycle, kg EPs	0.05	0.5	5.4
Rate of EPs removal, g EPs/h	1.8	17.8	178.1
Required time for regenerating the solution in PL, d		1.3	
Installed PL power, kW	42	417	4167
Equivalent electrical consumption, kWh/d	16	158	1579
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year	759	7586	75,858
Installed peak PV power, kWp	389	3893	38,929
Production cost (LCOE), EUR/kWh	0.093	0.077	0.063
PV plant installation (YES/NO)	YES	YES	YES
PV plant production, MWh/year	606	6063	60,632
Net cost of consumed electricity (averaged), EUR/kWh	0.108	0.101	0.095

Case C. The system is applied in a WWTP, which already has an advanced treatment for removing suspended solids after the secondary treatment and where the treated water is discharged into a water body. The treatment system is similar to Case A but excludes the first stage consisting of direct filtration + ultrafiltration because that treatment is supposed to be carried out by the current facilities. As in Case A, the objective is to limit the presence of EPs in the mentioned water body.

Case D. The system applied in a WWTP, which already has a tertiary treatment for reclaiming water, but does not have a special treatment for EPs removal. The objective is to implement only the adsorption with CDs followed by photocatalysis stages, using them along with the rest of current tertiary treatment stages, for reclaiming water. The treatment is similar to Case B but excludes the first stage consisting of direct filtration + ultrafiltration because that treatment is supposed to be carried out by the current facilities. Therefore, new facilities are similar to those of Case C. Table 7 includes the results obtained for Cases C and D. The data regarding the operation of the existing reclamation facilities are not included.

Table 7. Results obtained in Cases C and D sizing.

WWTP Influent, m^3/d	1000	10,000	100,000
CDs adsorption stage			
CDs adsorption influent, m^3/d	1000	10,000	100,000
EPs removal performance, %			28
Required amount of CDs, ton	9.5	95	950
Volume of water treated per adsorption cycle, m^3	40,280	402,800	4,028,000
Time to complete 1 adsorption cycle, d		40	
Time until replacement of exhausted CDs, d	403		

Table 7. *Cont.*

WWTP influent, m^3/d	1000	10,000	100,000
CDs adsorption stage			
Amount of adsorbed EPs until the replacement of exhausted CDs, kg	0.54	5.4	54.4
Equivalent CDs dose, mg/L		24	
Equivalent CDs consumption, kg/d	24	236	2358
Maximum adsorption capacity of EPs, mgEPs/gCDs		0.0057	
Electrical consumption, kWh/d	60	600	6000
Photocatalysis stage			
Photocatalysis influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		74	
EPs removal performance (CDs + PH), %		81	
Electrical consumption, kWh/d	1700	17,000	170,000
CDs regeneration stage			
Required amount of regenerant solution, m^3	7.1	71	713
Equivalent consumption of regenerant solution, L/d	18	177	1769
Equivalent electrical consumption, kWh/d	0.001	0.007	0.071
Pulsed light stage			
Regenerant to treat per adsorption cycle, m^3	7.1	71.3	713
EPs concentration in regenerant solution to recover, mg/L		8.0	
EPs to remove in PL system per adsorption cycle, kg EPs	0.05	0.5	5.4
Rate of EPs removal, g EPs/h	1.8	17.8	178.1
Required time for regenerating the solution in PL, d		1.3	
Installed PL power, kW	42	417	4167
Equivalent electrical consumption, kWh/d	16	158	1579
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year	648	6482	64,816
Installed peak PV power, kWp	333	3326	33,263
Production cost (LCOE), EUR/kWh	0.094	0.078	0.064
PV plant installation (YES/NO)	YES	YES	YES
PV Plant production, MWh/year	518	5181	51,806
Net cost of consumed electricity (averaged), EUR/kWh	0.109	0.101	0.095

Cases A and B assume that the WWTP does not have any tertiary treatment for the removal of suspended solids and turbidity, so this treatment must be included as a first step by the Clean Up system, so that the subsequent stages of EPs removal and disinfection may work properly. The proposed treatment in these cases is direct filtration (microfiltration) followed by ultrafiltration, which is similar to the one included at the Clean Up pilot plant. It must be considered that the UF is an expensive treatment, as compared to other tertiary treatments, both at an operational level and investment level. Thus, the use of UF as a treatment stage of the Clean Up system could not be justified in a technical–economic term, both if the objective is to discharge the treated effluent into the water bodies or whether it serves to reclaim water. It must be noted that in the field of water reclamation, the UF is only used in those cases in which high-quality water is required, along with total removal of Escherichia coli (residential urban use or cooling towers, for example), but in most expected

uses for reclaimed water, such as agriculture, urban services or industrial processes, the required quality can be obtained through a physicochemical stage (P&C), followed by direct filtration (sand filters, microscreens or cloth filters) and a final disinfection stage with UV radiation, or simply through direct filtration followed by UV disinfection [53]. In fact, the treatment technology which has been considered an alternative to the Clean Up system, which is later compared to the Clean Up in economic terms, also needs a first stage for suspended solids and turbidity removal, for optimizing the later EPs removal and disinfection stages. However, it has been found that this tertiary treatment can be carried out by technologies such as the ones indicated in previous paragraphs. Finally, the selected tertiary treatment depends on the quality of the secondary effluent and the quality required for the treated water, according to its forecasted use or following treatment stages. Thus, depending on the concentration and characteristics of the particles and colloids in the secondary effluent, it is possible that these indicated technologies can ensure the proper performance of the adsorption stage, not necessarily the use of a UF stage. For this reason, additional study cases are now proposed, so that the possible technical scenarios are reflected. These cases are named A′ and B′, as they would be applied in the same scenario cases as Cases A and B, but substituting now the microfiltration + ultrafiltration stage for conventional tertiary treatment.

Case A′. The system is similar to Case A; that is, it is applied in a WWTP, which does not have any advanced treatment for removing suspended solids after its secondary settlers, and where the treated water is discharged into a water body. The objective is to limit the presence of EPs in the mentioned water body. The treatment system is composed then by all the elements included in the pilot plant with the exception of the micro and ultrafiltration stages. These are substituted by a direct filtration stage, as explained below.

Direct filtration stage. This stage is designed for treating the water coming from the secondary settlers, with the aim of limiting the number of undissolved solids that reach the adsorption stage. There are different treatment trains for reaching this objective, depending basically on the quality of the secondary effluent. In this case, it is assumed that the quality of the secondary effluent is high enough to require only a direct filtration stage as a tertiary treatment. This direct filtration system is calculated as an average of microscreens, cloth filters and sand filters (open and closed), all commonly used in tertiary treatments. Then, the considered calculation parameters are the following: (i) TSS in secondary effluent—15 mg/L; (ii) recovery—98% (the remaining 2% of water is used in cleaning operations and is after led to the inlet of the WWTP, as its TSS concentration is similar to that of the WWTP influent; (iii) TSS removal performance—55%; and (iv) electrical consumption—0.15 kWh/m^3.

The concentrate produced in cleaning operations is directed to the inlet of the WWTP. For this reason, the direct filtration stage is sized considering the treatment capacity increase that this recirculated volume supposes. Table 8 includes the results obtained for Case A′.

Table 8. Results obtained in Case A′ sizing.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Direct filtration stage			
Filtration influent, m^3/d	1020	10,204	102,041
Filtration effluent, m^3/d		1000	
TSS in filtration effluent, mg/L		6.9	
Wastewater flow (from filter cleaning), m^3/d	20	204	2041
TSS in wastewater from filter cleaning, mg/L		413	
Electrical consumption, kWh/d	153	1531	15,306
CDs adsorption stage			
CDs adsorption influent, m^3/d	1000	10,000	100,000

Table 8. *Cont.*

WWTP Influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		28	
Required amount of CDs, ton		9.5	
Volume of water treated per adsorption cycle, m^3	40,280	402,800	4,028,000
Time to complete 1 adsorption cycle, d		40	
Time until replacement of exhausted CDs, d		403	
Amount of adsorbed EPs until the replacement of exhausted CDs, kg	0.54	5.4	54.4
Equivalent CDs dose, mg/L		24	
Equivalent CDs consumption, kg/d		24	
Maximum adsorption capacity of EPs, mgEPs/gCDs		0.0057	
Electrical consumption, kWh/d	60	600	6000
Photocatalysis stage			
Photocatalysis influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		74	
EPs removal performance (CDs + PH), %		81	
Electrical consumption, kWh/d	1700	17,000	170,000
CDs regeneration stage			
Required amount of regenerant solution, m^3		7.1	
Equivalent consumption of regenerant solution, L/d	18	177	1769
Equivalent electrical consumption, kWh/d	0.001	0.007	0.071
WWTP influent, m^3/d		1000	
Pulsed light stage			
Regenerant to treat per adsorption cycle, m^3	7.1	71.3	713
EPs concentration in regenerant solution to recover, mg/L		8.0	
EPs to remove in PL system per adsorption cycle, kg EPs	0.05	0.5	5.4
Rate of EPs removal, g EPs/h	1.8	17.8	178.1
Required time for regenerating the solution in PL, d		1.3	
Installed PL power, kW	42	417	4167
Equivalent electrical consumption, kWh/d	16	158	1579
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year	704	7040	70,403
Installed peak PV power, kWp	361	3613	36,130
Production cost (LCOE), EUR/kWh	0.094	0.077	0.063
PV plant installation (YES/NO)	YES	YES	YES
PV Plant production, MWh/year	563	5627	56,272
Net cost of consumed electricity (averaged), EUR/kWh	0.108	0.101	0.095

Case B'. The system is similar to Case B; that is, it is applied in a WWTP that does not have any advanced treatment for removing suspended solids after its secondary treatment, and where the aim is to reclaim water for being used in agriculture, including the removal of EPs in the water reclamation process. The treatment system is composed of all the elements included in the pilot plant with the exception of the micro and ultrafiltration

stages. These are substituted by a direct filtration stage, as has been explained in Case A'. Additionally, the system includes a final chlorination step (NaClO dosing) to maintain a minimum residual oxidant in the reclaimed water. Table 9 includes the results obtained for Case B'.

Table 9. Results obtained in Case B' sizing.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Direct filtration stage			
Filtration influent, m^3/d	1020	10,204	102,041
Filtration effluent, m^3/d		1000	
TSS in filtration effluent, mg/L		6.9	
Wastewater flow (from filter cleaning), m^3/d	20	204	2041
TSS in wastewater from filter cleaning, mg/L		413	
Electrical consumption, kWh/d	153	1531	15,306
CDs adsorption stage			
CDs adsorption influent, m^3/d	1000	10,000	100,000
EPs removal performance, %		28	
Required amount of CDs, ton		9.5	
Volume of water treated per adsorption cycle, m^3	40,280	402,800	4,028,000
Time to complete 1 adsorption cycle, d		40	
Time until replacement of exhausted CDs, d		403	
Amount of adsorbed EPs until the replacement of exhausted CDs, kg	0.54	5.4	54.4
Equivalent CDs dose, mg/L		24	
WWTP influent, m^3/d		1000	
CDs adsorption stage			
Equivalent CDs consumption, kg/d	24	236	2358
Maximum adsorption capacity of EPs, mgEPs/gCDs		0.0057	
Electrical consumption, kWh/d	60	600	6000
Photocatalysis stage			
Photocatalysis influent, m^3/d		1000	
EPs removal performance, %		74	
EPs removal performance (CDs + PH), %		81	
Electrical consumption, kWh/d		1700	
Chlorination stage			
Disinfection influent, m^3/d	1000	10,000	100,000
NaClO consumption (50% solution), kg/d		13	
CDs regeneration stage			
Required amount of regenerant solution, m^3	7.1	71	713
Equivalent consumption of regenerant solution, L/d		18	
Equivalent electrical consumption, kWh/d	0.001	0.007	0.071
Pulsed light stage			
Regenerant to treat per adsorption cycle, m^3		7.1	

Table 9. *Cont.*

WWTP Influent, m^3/d	1000	10,000	100,000
EPs concentration in regenerant solution to recover, mg/L		8.0	
EPs to remove in PL system per adsorption cycle, kg EPs	0.05	0.5	5.4
Rate of EPs removal, g EPs/h	1.8	17.8	178.1
Required time for regenerating the solution in PL, d		1.3	
Installed PL power, kW	42	417	4167
Equivalent electrical consumption, kWh/d	16	158	1579
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year	704	7040	70,403
Installed peak PV power, kWp	361	3613	36,130

2.4. Capital Costs

Once the different treatments considered are sized, the following step is the calculation of the corresponding treatment costs. The necessary investment depends on the studied case, as the considered technologies may vary from case to case. For part of the assessed technologies (adsorption on cyclodextrins, photocatalysis and pulsed light), no industrial plant that can serve as a reference exists, so it is difficult to define the investment cost of these technologies at that scale. The only reference available is the cost estimation of the project's pilot plant, which can be seen in Table 10.

Table 10. Cost estimation of the Clean Up pilot plant.

Item	Cost, EUR
Pilot plant materials	37,906
Pulsed light system	53,496
Civil work	9520
Photovoltaic plant	32,732
Photocatalysis equipment	8461
Total	142,115

Using these data, a methodology for estimating the investment costs as a function of the treatment capacity of the facilities has been established, within the range assessed in the study (from 1000 to 100,000 m^3/d). For the cost estimation of the pilot plant (Table 10), the following points must be considered: (i) in the cases where the treatment plant does not include treatment of MF + UF (cases C, D, A' and B'); (ii) in the cases where the treatment plant includes a final step for chlorination (cases B and B'), the investment costs for said step included in Table 11 are considered; and (iii) in the cases where a first stage of direct filtration, as tertiary treatment, is included, it is calculated as an average of microscreens, cloth filters and sand filters (cases A' and B'), and the investment costs for that step included in Table 11 are considered.

The investment calculated in each case from the data in Table 10, and the aspects indicated in the previous point is increased a 30% for auxiliary materials, assembly and installation. The result corresponds to the material execution of the project in each case. From the obtained material execution, the benefit rate and general expenses are added in all cases, obtaining the cost basis, that is, the investment cost excluding VAT tax. From the cost basis and considering the treatment capacity of the pilot plant (3 m^3/h) as a reference, the investment (cost basis) of 1000 m^3/d is calculated using the rule of 6.10. This rule has its origin in the relationship between the increase in equipment cost and the increase in capacity [54]. As a general rule, this can be used for estimating the cost associated with a capacity from the cost of the same facility but with other capacities, with an error not higher than 20%. Once the investment cost of the 1000 m^3/d plant is known for all the

foreseen cases, those of the 10,000 and 100,000 m^3/d are also calculated, considering this a variation in investment costs with respect to the treatment capacity for said interval that is similar to that of other conventional tertiary treatment technologies.

Table 11. Information considered for capital cost calculation.

WWTP Influent, m^3/d		**1000**	**10,000**	**100,000**
Investment costs EUR/m^3/d	Final chlorination (Cases B and B′)	45	41	37
	Direct filtration (Cases A′ and B′)	125	175	50
Benefit rate, % [1]			6	
General expenses rate, % [1]			13	
VAT, %			21	
Investment lifetime, years			20	
Financing interest, %			5	

Note: [1] Applied over material execution.

Table 11 gathers all the information considered for the calculation of the capital costs, based on the studied cases and the treatment capacity of the facilities. For the investment costs of the final chlorination and direct filtration stages, several references have been revised: [43,49,51,55–61].

Tables 12–16 show the results of the capital costs calculation. Capital costs are calculated based on the basis values, as it has been assumed that the investment would be carried out by the public sector.

Table 12. Capital costs calculated for Case A.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment costs EUR/m^3/d	821	423	284
Investment, EUR	992,874	5,114,805	34,385,246
Investment (basis), EUR	820,557	4,227,112	28,417,558
Material execution, EUR	689,268	3,550,774	23,870,749
Capital costs, EUR/year	65,844	339,194	2,280,298
Capital costs, EUR/m^3	0.18	0.09	0.06

Table 13. Capital costs calculated for Case B.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment costs EUR/m^3/d	866	464	321
Investment, EUR	1,047,324	5,610,905	38,862,246
Investment (basis), EUR	865,557	4,637,112	32,117,558
Material execution, EUR	727,068	3,895,174	26,978,749
Capital costs, EUR/year	69,455	372,094	2,577,196
Capital costs, EUR/m^3	0.19	0.10	0.07

It is assumed that the overall objective of the investments is to achieve significant removals of micropollutants in the WWTP, whatever the destination of the treated water is, as a response to a risk to human health. For that reason, it is considered that the investment is undertaken by the public sector, as said. However, it should not be forgotten that part of the investment has the objective of removing pathogens, as a necessary step for reclaiming water, as can be seen in cases B and B′. In those cases, the additional treatments to the ones

that are considered for the EP removal can be paid for by the end users of the reclaimed waters. For doing so, a price for reclaimed water that defrays the capital and operational cost of that disinfection stage can be fixed, maintaining a null benefit, as it is a public service. This situation is assumed, but not included in the costs analysis, since it would be similar in all the studied cases (Clean Up system and alternatives), so it would not affect the results of the economic analysis.

Table 14. Capital costs calculated for Cases C&D.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment costs EUR/m^3/d	593	305	205
Investment, EUR	717,502	3,696,223	24,848,560
Investment (basis), EUR	592,977	3,054,730	20,536,000
Material execution, EUR	498,101	2,565,973	17,250,240
Capital costs, EUR/year	47,582	245,119	1,647,862
Capital costs, EUR/m^3	0.13	0.07	0.05

Table 15. Capital costs calculated for Case A′.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment costs EUR/m^3/d	718	380	255
Investment, EUR	868,752	4,603,723	30,898,560
Investment (basis), EUR	717,977	3,804,730	25,536,000
Material execution, EUR	603,101	3,195,973	21,450,240
Capital costs, EUR/year	57,612	305,301	2,049,075
Capital costs, EUR/m^3	0.16	0.08	0.06

Table 16. Capital costs calculated for Case B′.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment costs EUR/m^3/d	763	421	292
Investment, EUR	923,202	5,099,823	35,375,560
Investment (basis), EUR	762,977	4,214,730	29,236,000
Material execution, EUR	640,901	3,540,373	24,558,240
Capital costs, EUR/year	61,223	338,201	2,345,972
Capital costs, EUR/m^3	0.17	0.09	0.06

2.5. Operational Costs

Below it is included all the information that has been used for carrying out the operational cost calculation, for each considered case. For that, the results obtained in the sizing of the different cases have been used (Tables 5–9), as well as information coming from real tertiary treatment facilities, regarding prices (chemicals, electricity cost, etc.), labor costs, maintenance costs, etc. The chemicals and costs considered in the study are the following: (i) membrane cleaning chemicals (applied in cases A and B) a cost of EUR 0.03 per m^3 treated in the ultrafiltration system is set up; (ii) β-Cyclodextrins (applied in all cases), considering all these factors a price of 5 EUR/kg is set up for βCDs; (iii) regenerant solution (applied in all cases), a price of 1 EUR/kg is set up; (iv) hypochlorite solution (cases B and B′), a price of 0.55 EUR/kg, assuming a 50% solution; and (v) the net energy cost is averaged for each case and included in Tables 5–9. Table 17 sums up that information.

Table 17. Averaged net costs of consumed electricity.

WWTP Influent, m^3/d		1000	10,000	100,000
Net cost of consumed electricity (averaged), EUR/kWh	Case A	0.108	0.101	0.095
	Case B			
	Cases C and D	0.109		
	Case A′	0.108		
	Case B′			

Labor costs depend on the treatment stages that every proposed case includes, and the treatment capacity of the facility. For the calculation, only labor costs associated with the operation of the new facilities are considered. Table 18 includes the considered labor costs.

Table 18. Calculated labor costs for Cases A, B, C, D, A′ and B′.

WWTP Influent, m^3/d		1000	10,000	100.000
Labor costs, EUR/year	Case A Case B	15,000	55,000	250,000
	Cases C and D	12,000	44,000	200,000
	Case A′ Case B′	15,000	55,000	250,000

Maintenance and conservation costs are assumed to be a yearly cost equivalent to 2% of the material execution of the investment. Regarding equipment replacement costs, it is assumed that it will be necessary to replace electro-mechanical equipment in the midterm of the investment lifetime, for which a cost equivalent to 30% of the material execution of the initial investment is applied. It is also assumed that this cost is distributed linearly throughout the investment lifetime, without considering any discount rate. Additionally, a cost due to the replacement of the photocatalysis and pulse light lamps is applied. For this concept, a cost of EUR 0.015 per m^3 treated in the photocatalysis system is set up. Administrative and analysis costs include all the additional costs not previously mentioned, as derived from the analytic control of waters or administrative expenses. It is supposed to be 3% of the operational costs (Table 19).

Table 19. Calculated administrative and analysis costs for Cases A, B, C, D, A′ and B′.

WWTP Influent, m^3/d		1000	10,000	100,000
Administrative and analysis costs, EUR/year	Case A	5800	50,000	460,000
	Case B	5900	51,000	470,000
	Cases C and D	4800	41,000	380,000
	Case A′	5100	44,000	410,000
	Case B′	5300	45,000	420,000

Tables 20–24 include the results of the operational costs calculation, depending on each studied case and the treatment capacity of the plant. These costs come only from the new treatment stages to be implemented, and they are referred to as the m^3 of produced water.

Table 20. Operational costs calculated for Case A.

WWTP Influent, m^3/d		1000	10,000	100,000
Chemicals	EUR/year EUR/m^3	62,381 0.17	623,812 0.17	6,238,117 0.17

Table 20. *Cont.*

WWTP Influent, m^3/d		1000	10,000	100,000
Electrical consumption	EUR/year EUR/m^3	81,992 0.22	764,108 0.21	7,182,144 0.20
Labor	EUR/year EUR/m^3	15,000 0.041	55,000 0.015	250,000 0.007
Maintenance and conservation	EUR/year EUR/m^3	13,785 0.038	71,015 0.019	477,415 0.013
Equipment replacement	EUR/year EUR/m^3	15,814 0.043	108,012 0.030	905,561 0.025
Administrative and analysis costs	EUR/year EUR/m^3	5800 0.016	50,000 0.014	460,000 0.013
Operational costs	EUR/year EUR/m^3	194,773 0.53	1,671,947 0.46	15,513,238 0.43

Table 21. Operational costs calculated for Case B.

WWTP Influent, m^3/d		1000	10,000	100,000
Chemicals	EUR/year EUR/m^3	64,913 0.178	649,127 0.178	6,491,267 0.178
Electrical consumption	EUR/year EUR/m^3	81,992 0.22	764,108 0.21	7,182,144 0.20
Labor	EUR/year EUR/m^3	15,000 0.041	55,000 0.015	250,000 0.007
Maintenance and conservation	EUR/year EUR/m^3	14,541 0.040	77,903 0.021	539,575 0.015
Equipment replacement	EUR/year EUR/m^3	16,381 0.045	113,178 0.031	952,181 0.026
Administrative and analysis costs	EUR/year EUR/m^3	5900 0.016	51,000 0.014	470,000 0.013
Operational costs	EUR/year EUR/m^3	198,727 0.80	1,710,316 0.73	15,885,167 0.69

Table 22. Operational costs calculated for Cases C&D.

WWTP Influent, m^3/d		1000	10,000	100,000
Chemicals	EUR/year EUR/m^3	49,499 0.136	494,988 0.136	4,949,882 0.136
Electrical consumption	EUR/year EUR/m^3	70,419 0.19	655,854 0.18	6,161,121 0.17
Labor	EUR/year EUR/m^3	12,000 0.033	44,000 0.012	200,000 0.005
Maintenance and conservation	EUR/year EUR/m^3	9962 0.027	51,319 0.014	345,005 0.009
Equipment replacement	EUR/year EUR/m^3	12,947 0.035	93,240 0.026	806,254 0.022
Administrative and analysis costs	EUR/year EUR/m^3	4800 0.013	41,000 0.011	380,000 0.010
Operational costs	EUR/year EUR/m^3	159,626 0.44	1,380,401 0.38	12,842,262 0.35

Table 23. Operational costs calculated for Case A′.

WWTP Influent, m^3/d		1000	10,000	100,000
Chemicals	EUR/year	49,499	494,988	4,949,882
	EUR/m^3	0.136	0.136	0.136
Electrical consumption	EUR/year	76,282	710,683	6,678,185
	EUR/m^3	0.21	0.19	0.18
Labor	EUR/year	15,000	55,000	250,000
	EUR/m^3	0.041	0.015	0.007
Maintenance and conservation	EUR/year	12,062	63,919	429,005
	EUR/m^3	0.033	0.018	0.012
Equipment replacement	EUR/year	14,522	102,690	869,254
	EUR/m^3	0.040	0.028	0.024
Administrative and analysis costs	EUR/year	5100	44,000	410,000
	EUR/m^3	0.014	0.012	0.011
Operational costs	EUR/year	172,464	1,471,280	13,586,326
	EUR/m^3	0.47	0.40	0.37

Table 24. Operational costs calculated for Case B′.

WWTP Influent, m^3/d		1000	10,000	100,000
Chemicals	EUR/year	52,030	520,303	5,203,031
	EUR/m^3	0.143	0.143	0.143
Electrical consumption	EUR/year	76,281	710,683	6,678,183
	EUR/m^3	0.21	0.19	0.18
Labor	EUR/year	15,000	55,000	250,000
	EUR/m^3	0.041	0.015	0.007
Maintenance and conservation	EUR/year	12,818	70,807	491,165
	EUR/m^3	0.035	0.019	0.013
Equipment replacement	EUR/year	15,089	107,856	915,874
	EUR/m^3	0.041	0.030	0.025
Administrative and analysis costs	EUR/year	5300	45,000	420,000
	EUR/m^3	0.015	0.012	0.012
Operational costs	EUR/year	176,518	1,509,649	13,958,252
	EUR/m^3	0.48	0.41	0.38

2.6. Total Costs

Table 25 includes the calculated costs for all cases. Several potential regressions have been fitted from the obtained results, which can be seen in Figure 2.

Table 25. Total costs calculated for all the studied cases (A, B, C, D, A′ and B′).

WWTP Influent, m^3/d		1000	10,000	100,000
Case A	Capital costs, EUR/m^3	0.18	0.09	0.06
	Operation costs, EUR/m^3	0.53	0.46	0.43
	Total costs, EUR/m^3	0.71	0.55	0.49
Case B	Capital costs, EUR/m^3	0.19	0.10	0.07
	Operation costs, EUR/m^3	0.54	0.47	0.44
	Total costs, EUR/m^3	0.73	0.57	0.51

Table 25. *Cont.*

WWTP Influent, m^3/d		1000	10,000	100,000
Cases C and D	Capital costs, EUR/m^3	0.13	0.07	0.05
	Operation costs, EUR/m^3	0.44	0.38	0.35
	Total costs, EUR/m^3	0.57	0.45	0.40
Case A′	Capital costs, EUR/m^3	0.16	0.08	0.06
	Operation costs, EUR/m^3	0.47	0.40	0.37
	Total costs, EUR/m^3	0.63	0.49	0.43
Case B′	Capital costs, EUR/m^3	0.17	0.09	0.06
	Operation costs, EUR/m^3	0.48	0.41	0.38
	Total costs, EUR/m^3	0.65	0.51	0.45

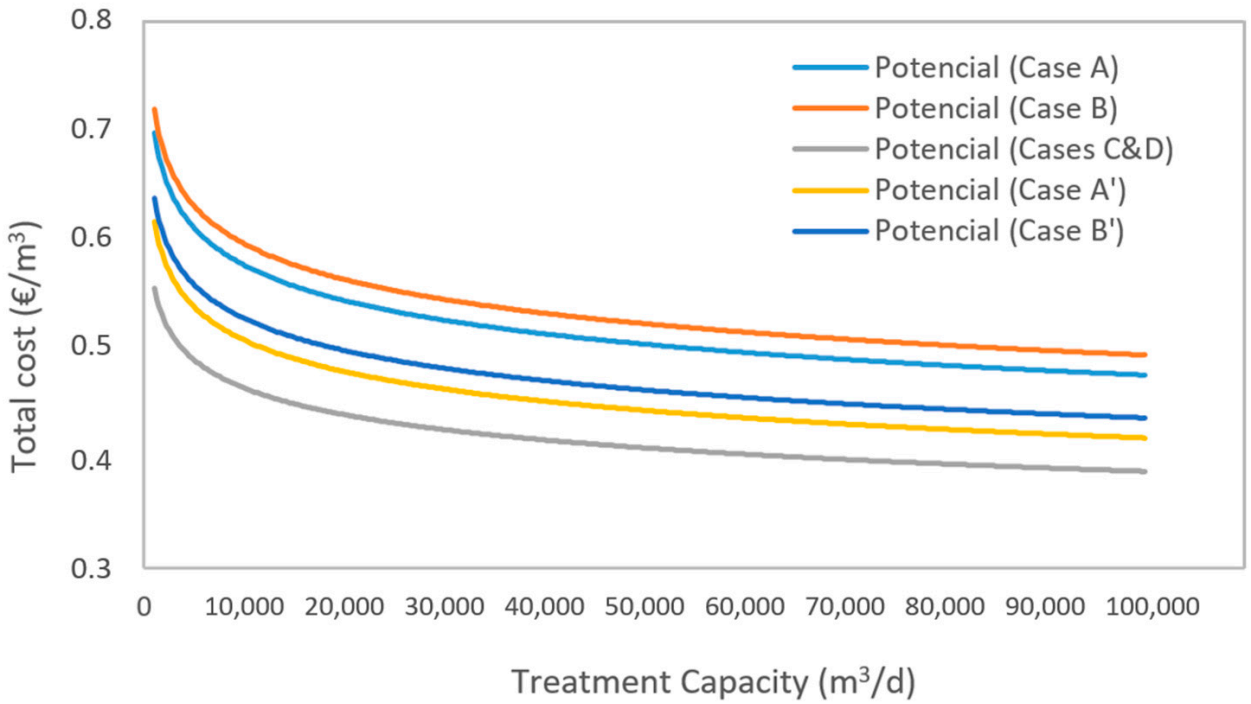
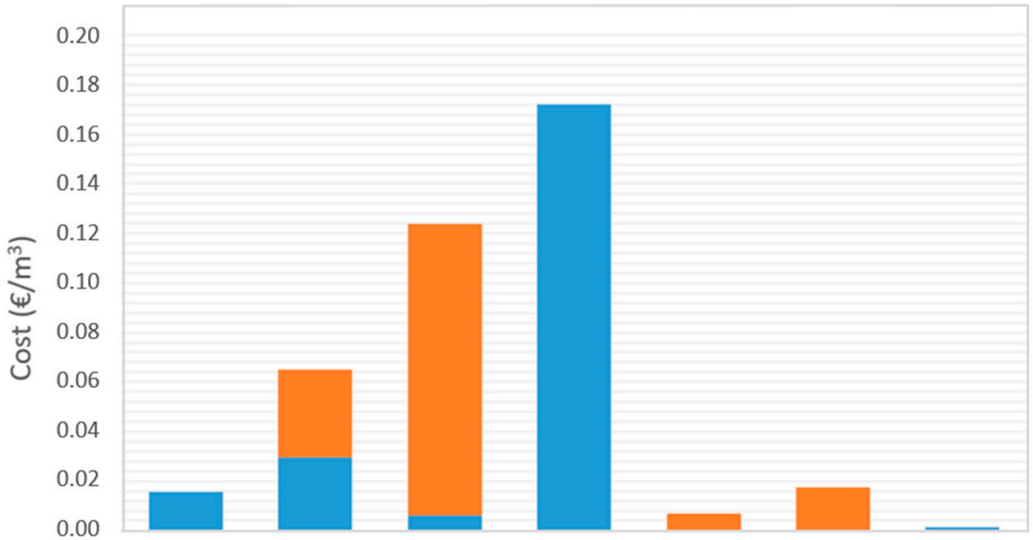


Figure 2. Total costs of all the studied cases. Data fitted to a potential regression.

The previous results clearly show that, for all the foreseen scenarios, the sum of the costs of chemicals and electrical consumption exceeds 73% of the operational costs and 54% of the total costs. Focusing on the analysis of these two operational costs, it can be determined which operations of all those that integrate into the water treatment system outweigh these costs. The values are averages calculated considering all the scenarios where these operations take place, as well as the different treatment capacities considered. Averages have been calculated instead of using values for each case separately because the variation in these costs for the different cases and capacities is not significant, so Figure 3 can represent all the studied cases. Particularly, it must be pointed out that filtration only applies in cases A′ and B′, and chlorination only in B and B′.



Cost (€/m3)	Filtration	MF + UF	Ads. CDs.	Photocat.	Chlorinat.	Rege CDs	P. Light
Elec. Consumption	0.016	0.029	0.006	0.172	< 0.001	< 0.001	0.001
Chemicals	< 0.001	0.036	0.118	0.001	0.007	0.017	< 0.001

Figure 3. Averaged treatment cost by treatment operation.

3. Results of Economic Feasibility Analysis

In this section, the procedures followed to calculate the treatment costs of the considered technical alternative to the Clean Up system are described, as well as the obtained results. Then, the technical–economic viability of the Clean Up solution is determined through the comparison between its treatment costs and the ones for the technical alternatives.

3.1. Treatment Costs of Technical Alternatives

The technical alternatives to the Clean Up solution, both from a technical and economic point of view, the most efficient ones are ozonation and PAC. These treatments must be applied in WWTPs that already have advanced treatments for nutrients and suspended solids removal so that this is effective. On the other hand, these treatments must also include a final filtration stage, after the O_3/PAC stage. That last stage can be a gravity sand filter including biofilm formation, in the case of the O_3. In the case of PAC, they could be used in sand filters, microscreens, cloth filters or even membranes of MF or UF. The efficiency of these two treatments is proven, so both are already being implemented at an industrial scale in WWTPs to avoid the incoming of micropollutants into water bodies. For this reason, these treatments and not others have been considered in principle as technical alternatives to the Clean Up treatment. In general, they offer similar EP removal performance (around 80%). Anyway, only the O_3 option has been finally considered as an alternative to Clean Up, finding the same application scenarios for both technologies. The PAC option has been discarded due to several disadvantages that emerge when compared to O_3. Summing up, PAC application entails the presence of exhausted PAC with EPs in the produced sewage sludge, which can limit its use in agriculture. Above this, the treatment with PAC is in general terms more expensive than the O_3 one. So, only the O_3 treatment is considered to be compared to the Clean Up treatment.

To estimate the treatment costs of the O_3 system, the same scenarios indicated previously for the Clean Up case have been considered, that is, application in WWTPs that either have an advanced treatment or not, and the aim to discharge treated water into water bodies or reclaim it to be used in agriculture. In addition, as in the Clean Up case, a treat-

ment capacity between 1000 and 100,000 m^3/d has been considered. The treatment system, whose costs are intended to be calculated, will have particular characteristics, depending on the application scenario and, therefore, also particular costs. Regarding the calculation parameters used for sizing these systems, the operational conditions, consumptions and performances that could be expected from said systems are described below. For setting up these data, general information obtained from various bibliographic sources is used. This information is later specified, in every case where it is used.

Case A*. The system is applied in a WWTP that does not have any advanced treatment for removing suspended solids after its secondary settlers, and where the treated water is discharged into a water body. Then, the objective is to limit the presence of EPs in the mentioned water body. The treatment system is composed of a first stage of tertiary treatment (filtration) for suspended solids removal, followed by the ozonation contact reactor and a final stage of high-rate biofiltration using inert media (sand). Below, it is described how the implementation at the industrial level of the different stages that compose this treatment would be completed, as well as the considerations that have been carried out for estimating the treatment costs of the mentioned system. The sources that have been consulted to define the previous design parameters are the following: [21–30,37,39,41–51,58,60,62,63].

In addition, this information has been verified with available data from real tertiary treatment facilities.

Direct filtration stage. This stage is designed for treating the water coming from secondary settlers, providing water with a concentration of both, suspended solids and dissolved organic carbon (DOC), lower than 10 ppm. There are different treatment trains for aiming this objective, depending basically on the quality of the secondary effluent. These systems are mainly composed of physicochemical and filtration treatments. In this case, it is assumed that the level of quality of the secondary effluent is high enough to only require a direct filtration stage as a tertiary treatment. This direct filtration system is calculated as an average of microscreens, cloth filters and sand filters (open and closed) all commonly used in tertiary treatments. Then, the considered calculation parameters are the following: (i) TSS in secondary effluent—15 mg/L; (ii) recovery—98%; (iii) TSS removal performance—55%; and (iv) electrical consumption—0.15 kWh/m^3. Both in the case of direct filtration and biofiltration stages, the concentrate produced in cleaning operations is directed to the inlet of the WWTP. For this reason, the direct filtration stage is sized considering the increase in the treatment capacity that these two recirculated volumes suppose, and for the biofiltration, the followed procedure is similar, but considering only the recirculate stream generated in said operation.

Ozonation stage. This stage is designed to oxidize the remaining organic matter present in the direct filtration effluent, including the micropollutants. The treatment supposes a micropollutant removal higher than 80%. These compounds are mainly mineralized to CO_2 and H_2O, being the remaining ones degraded to oxidation by-products, which are less toxic and more biodegradable, so they are removed in the final biofiltration stage. For sizing the ozonation stage, the considered calculation parameters are the following: (i) DOC in secondary effluent—7.5 mg/L; (ii) O_3 dose—5 mg/L; (iii) electrical consumption for ozone generation 12.5 kWh/kgO_3; (iv) electrical consumption for water pumping 0.03 kWh/m^3; and (v) EPs removal performance—80% (ozonation + biofiltration).

Biofiltration stage. In this stage, the ozonation by-products and residual organic compounds are removed. It is a slow gravity filtration through an inert granular media (sand), in which the organic compounds are removed by the biofilm that grows over the surface of the media. That biofilm grows in the upper zone of the filter, where the sand is in contact with oxygenated water. The biofilters are cleaned regularly, and the wastewater produced in said operation goes to the WWTP inlet. The calculation parameters used for biofiltration sizing are the following: (i) recovery—98%; (ii) TSS removal performance—60%; (iii) EPs removal performance—80% (ozonation + biofiltration); and (iv) electrical consumption—0.05 kWh/m^3. Table 26 includes the results obtained for Case A*.

Table 26. Results obtained in Case A* sizing.

WWTP Influent, m^3/d	1000	10,000	100,000
Direct filtration stage			
Filtration influent, m^3/d	1041	10,412	104,123
Filtration effluent, m^3/d			
TSS in filtration effluent, mg/L		6.9	
Wastewater flow (from filter cleaning), m^3/d	21	208	2082
TSS in wastewater from filter cleaning, mg/L		412	
Electrical consumption, kWh/d	156	1562	15,618
WWTP influent, m^3/d	1000	10,000	100,000
Ozonation stage			
Ozonation influent, m^3/d	1020	10,204	102,041
TSS in ozonation influent, mg/L			
Electrical consumption, kWh/d		94	
Biofiltration stage			
Biofiltration influent, m^3/d		1020	
TSS in biofiltration influent, mg/L		6.9	
Biofiltration effluent, m^3/d		1000	
TSS in biofiltration effluent, mg/L		2.8	
Wastewater flow (from filter cleaning), m^3/d		20	
TSS in wastewater from filter cleaning, mg/L		207	
Electrical consumption, kWh/d		51	
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year		110	
Installed peak PV power, kWp		56.5	
Production cost (LCOE), EUR/kWh		0.110	
PV plant installation (YES/NO)	YES	YES	YES
PV Plant production, MWh/year		88	
Net cost of consumed electricity (averaged), EUR/kWh	0.115	0.107	0.100

Case B*. The system is applied in a WWTP that does not have any advanced treatment for removing suspended solids after its secondary settlers, and where the aim is to reclaim water to be used in agriculture, including the removal of EPs in the water reclamation process. The treatment system is similar to Case A*, but includes a final stage consisting of UV disinfection, and a final chlorination step (NaClO dosing) to maintain a minimum residual in the reclaimed water. The calculation parameters used are similar to the previous case, and for the final disinfection stage, they are described below:

Disinfection stage. The stage is composed of irradiation by UV lamps and the subsequent stage of chlorination by NaClO dosing in a contact reactor. The objective is to reach the quality parameters set up by the current regulation (Regulation (EU) 2020/741) regarding the presence of pathogens in reclaimed water. The calculation parameters used are the following: (i) electrical consumption of 0.06 kWh/m^3 (it includes the UV lamps and the rest of the equipment) and (ii) NaClO dose of 3 gCl_2/m^3. Table 27 includes the results obtained for Case B*.

Table 27. Results obtained in Case B* sizing.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Direct filtration stage			
Filtration influent, m^3/d	1041	10,412	104,123
Filtration effluent, m^3/d			
TSS in filtration effluent, mg/L		6.9	
Wastewater flow (from filter cleaning), m^3/d		21	
TSS in wastewater from filter cleaning, mg/L		412	
Electrical consumption, kWh/d		156	
Ozonation stage			
Ozonation influent, m^3/d		1020	
TSS in ozonation influent, mg/L		6.9	
Electrical consumption, kWh/d		94	
Biofiltration stage			
Biofiltration influent, m^3/d		1020	
TSS in biofiltration influent, mg/L		6.9	
Biofiltration effluent, m^3/d		1000	
TSS in biofiltration effluent, mg/L		2.8	
Wastewater flow (from filter cleaning), m^3/d	20	204	2041
TSS in wastewater from filter cleaning, mg/L		207	
Electrical consumption, kWh/d	51	510	5102
Disinfection stage			
Disinfection influent, m^3/d	1000	10,000	100,000
TSS in biofiltration effluent, mg/L	2.8		
NaClO consumption (50% solution), kg/d	13	126	1261
Electrical consumption, kWh/d	60	600	6000
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year	132	1320	13,198
Installed peak PV power, kWp	67.7	677.3	6773.0
Production cost (LCOE), EUR/kWh	0.108	0.089	0.073
PV plant installation (YES/NO)	YES	YES	YES
PV plant production, MWh/year	105	1055	10,549
Net cost of consumed electricity (averaged), EUR/kWh	0.115	0.106	0.099

Case C*. The system is applied in a WWTP that already has an advanced treatment for removing suspended solids after its secondary settlers, and where the treated water is discharged into a water body. The treatment system is similar to Case A*, but excluding the first stage consisting of direct filtration, because that treatment is supposed to be carried out by the current facilities. As of Case A*, the objective is to limit the presence of EPs in the mentioned water body.

Case D*. The system applied in a WWTP that already has a tertiary treatment for reclaiming water, but the same does not have a special treatment for EP removal. The objective is to implement only the ozonation and biofiltration stages, using them along with the rest of the current tertiary treatment stages, for reclaiming water. The treatment is

similar to Case B*, but excluding the direct filtration and final disinfection stages, because that treatment is supposed to be carried out by the current facilities. Therefore, new facilities are similar to that of Case C*. Table 28 includes the results obtained for Cases C* and D*. The data regarding the operation of the existing reclamation facilities are not included.

Table 28. Results obtained in Cases C* and D* sizing.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Ozonation stage			
Ozonation influent, m^3/d	1020	10,204	102,041
TSS in ozonation influent, mg/L			
Electrical consumption, kWh/d		94	
Biofiltration stage			
Biofiltration influent, m^3/d		1020	
TSS in biofiltration influent, mg/L		6.9	
Biofiltration effluent, m^3/d		1000	
TSS in biofiltration effluent, mg/L		2.8	
Wastewater flow (from filter cleaning), m^3/d		20	
TSS in wastewater from filter cleaning, mg/L		207	
Electrical consumption, kWh/d		51	
Photovoltaic plant			
Electrical consumption of treatment plant, MWh/year		53	
Installed peak PV power, kWp		27.2	
Production cost (LCOE), EUR/kWh		0.117	
PV plant installation (YES/NO)	YES	YES	YES
PV plant production, MWh/year		42	
Net cost of consumed electricity (averaged), EUR/kWh	0.119	0.109	0.102

Once the different treatments considered are sized, the following step is the calculation of the corresponding treatment costs. Parameters and factors used for cost calculation and the obtained results are shown below. This work is divided into two sections: capital costs and operational costs.

Capital costs. The necessary investment depends on the studied case. Table 29 gathers all the information considered for the calculation of capital costs, based on the studied case and the treatment capacity of the facilities. For defining the investment costs, several references have been revised [43,49,51,55–61]:

Tables 30–32 show the results of the capital costs calculation, for Cases A*, B* and C*&D*, respectively. Capital costs are calculated based on the basis values (values excluding VAT), as it has been assumed that the investment would be carried out by the public sector.

Operational costs. All the information that has been used for carrying out the operational cost calculation for each considered case is included below. For doing so, the same information sources previously indicated have been used for the capital costs calculation, as well as information coming from real treatment facilities. (i) Chemicals cost is only applied in Case B*, as it is the only case for which it is necessary to implement new equipment for disinfection. The cost is due to the NaClO consumption, which is used for assuring a chlorine residual concentration in treated waters. The price set up for hypochlorite is 0.55 EUR/kg, assuming a 50% solution. (ii) Energy costs for each case depend on the consumption of electrical energy and the grade of the implementation of the PV system.

The net cost of consumed electricity is averaged for each case and included in Tables 26–28. Table 33 summarizes that information.

Table 29. Information considered for capital cost calculation for Cases A*, B*, C* and D*.

WWTP Influent, m^3/d		**1000**	**10,000**	**100,000**
Investment costs, EUR/m^3/d	Case A*	1145	595	400
Investment costs, EUR/m^3/d	Case B*	1275	670	455
Investment costs, EUR/m^3/d	Cases C* and D*	1020	520	350
Benefit rate, % [1]		6		
General expenses rate, % [1]		13		
VAT, %		21		
Investment lifetime, years		20		
Financing interest, %		5		

Note: [1] Applied over material execution.

Table 30. Capital costs calculated for Case A*.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment, EUR	1,275,000	6,700,000	45,500,000
Investment (basis), EUR	1,053,719	5,537,190	37,603,306
Material execution, EUR	885,124	4,651,240	31,586,777
Capital costs, EUR/year	84,553	444,318	3,017,387
Capital costs, EUR/m^3	0.23	0.12	0.08

Table 31. Capital costs calculated for Case B*.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment, EUR	1,145,000	5,950,000	40,000,000
Investment (basis), EUR	946,281	4,917,355	33,057,851
Material execution, EUR	794,876	4,130,579	27,768,595
Capital costs, EUR/year	75,932	394,581	2,652,648
Capital costs, EUR/m^3	0.21	0.11	0.07

Table 32. Capital costs calculated for Cases C* and D*.

WWTP Influent, m^3/d	**1000**	**10,000**	**100,000**
Investment, EUR	1,020,000	5,200,000	35,000,000
Investment (basis), EUR	842,975	4,297,521	28,925,620
Material execution, EUR	708,099	3,609,917	24,297,521
Capital costs, EUR/year	67,643	344,844	2,321,067
Capital costs, EUR/m^3	0.19	0.09	0.06

Table 33. Averaged net costs of consumed electricity for Cases A*, B*, C* and D*.

WWTP Influent, m^3/d		**1000**	**10,000**	**100,000**
Net cost of consumed electricity (averaged), EUR/kWh	Case A*	0.115	0.107	0.100
	Case B*	0.115	0.106	0.099
	Cases C* and D*	0.119	0.109	0.102

Labor costs depend on the treatment stages that every proposed case includes, and the treatment capacity of the facility. For the calculation, only labor costs associated with the operation of the new facilities are considered. Table 34 includes the considered labor costs.

Table 34. Calculated labor costs for Cases A*, B*, C* and D*.

WWTP Influent, m^3/d		1000	10,000	100,000
Labor costs, EUR/year	Case A*	15,000	55,000	250,000
	Case B*			
	Cases C* and D*	12,000	44,000	200,000

Maintenance and conservation costs are assumed to be a yearly cost equivalent to 2% of the material execution of the investment. It is assumed that regarding equipment replacement costs in the midterm of the investment lifetime, it is necessary to replace electro-mechanical equipment, for which a cost equivalent to 30% of the material execution of the initial investment is applied. It is also assumed that this cost is distributed linearly throughout the investment lifetime, without considering any discount rate. In addition, for the option that entails the implementation of a disinfection stage (case B*), a cost due to the replacement of the UV lamps of EUR 0.01 per treated m3 is assumed to take place. Finally, administrative and analysis costs include all the additional costs not previously mentioned, as derived from the analytic control of waters or administrative expenses. It is supposed to be 3% of the operational costs (Table 35).

Table 35. Calculated administrative and analysis costs for Cases A*, B*, C* and D*.

WWTP Influent, m^3/d		1000	10,000	100,000
Administrative and analysis costs, EUR/year	Case A*	1700	9900	72,000
	Case B*	2100	13,000	102,000
	Cases C* and D*	1350	7000	50,000

Tables 36–38 include the results of the operational costs calculation, depending on each studied case and the treatment capacity of the plant. These costs come only from the new treatment stages to implement, and they refer to the m^3 of produced water.

Table 36. Operational costs calculated for Case A*.

WWTP Influent, m^3/d		1000	10,000	100,000
Electrical consumption	EUR/year	12,711	117,563	1,097,160
	EUR/m^3	0.035	0.032	0.030
Labor	EUR/year	15,000	55,000	250,000
	EUR/m^3	0.041	0.015	0.007
Maintenance and conservation	EUR/year	15,898	82,612	555,372
	EUR/m^3	0.044	0.023	0.015
Equipment replacement	EUR/year	11,923	61,959	416,529
	EUR/m^3	0.033	0.017	0.011
Administrative and analysis costs	EUR/year	1700	9900	72,000
	EUR/m^3	0.005	0.003	0.002
Operational costs	EUR/year	57,231	327,034	2,391,061
	EUR/m^3	0.16	0.09	0.07

Table 37. Operational costs calculated for Case B*.

WWTP Influent, m^3/d		**1000**	**10,000**	**100,000**
Chemicals	EUR/year	2531	25,315	253,149
	EUR/m^3	0.007	0.007	0.007
Electrical consumption	EUR/year	15,141	140,142	1,308,772
	EUR/m^3	0.041	0.038	0.036
Labor	EUR/year	15,000	55,000	250,000
	EUR/m^3	0.041	0.015	0.007
Maintenance and conservation	EUR/year	17,702	93,025	631,736
	EUR/m^3	0.048	0.025	0.017
WWTP influent, m^3/d	1000	10,000	100,000	
Equipment replacement	EUR/year	16,927	106,269	838,802
	EUR/m^3	0.046	0.029	0.023
Administrative and analysis costs	EUR/year	2100	13,000	102,000
	EUR/m^3	0.006	0.004	0.003
Operational costs	EUR/year	69,402	432,750	3,384,459

Table 38. Operational costs calculated for Cases C*&D*.

WWTP Influent, m^3/d		**1000**	**10,000**	**100,000**
Electrical consumption	EUR/year	6294	58,043	540,174
	EUR/m^3	0.017	0.016	0.015
Labor	EUR/year	12,000	44,000	200,000
	EUR/m^3	0.033	0.012	0.005
Maintenance and conservation	EUR/year	14,162	72,198	485,950
	EUR/m^3	0.039	0.020	0.013
Equipment replacement	EUR/year	10,621	54,149	364,463
	EUR/m^3	0.029	0.015	0.010
Administrative and analysis costs	EUR/year	1350	7000	50,000
	EUR/m^3	0.004	0.002	0.001
Operational costs	EUR/year	44,427	235,390	1,640,587
	EUR/m^3	0.12	0.06	0.04

Total costs. Table 39 includes the calculated costs for cases A, B and C&D, respectively.

Table 39. Total costs calculated for all the studied Cases A*, B*, C* and D*.

WWTP Influent, m^3/d		**1000**	**10,000**	**100,000**
Case A*	Capital costs, EUR/m^3	0.21	0.11	0.07
	Operation costs, EUR/m^3	0.16	0.09	0.07
	Total costs, EUR/m^3	0.36	0.20	0.14
Case B*	Capital costs, EUR/m^3	0.23	0.12	0.08
	Operation costs, EUR/m^3	0.19	0.12	0.09
	Total costs, EUR/m^3	0.42	0.24	0.18
Cases C* and D*	Capital costs, EUR/m^3	0.19	0.09	0.06
	Operation costs, EUR/m^3	0.12	0.06	0.04
	Total costs, EUR/m^3	0.31	0.16	0.11

3.2. Comparative Cost Study

Once the treatment costs of both the Clean Up system and the proposed alternative have been analyzed, and for all the contemplated scenarios, the comparison of the costs of both systems allows us to know whether the Clean Up solution is competitive compared to the alternative in each scenario or not. In this sense, when comparing Tables 25 and 39, it is observed that in all cases, the total costs of the Clean Up solution are higher than those of the alternatives discussed in previous sections. A more detailed analysis of the results shows that, although the investment costs of the Clean Up system are lower than those of the alternative in all scenarios, the operational costs are much higher. Focusing the analysis on the operational costs of the Clean Up system, it is observed that the factors with the most influence are the electrical consumption of the photocatalytic stage, the chemicals used in the adsorption stage (cyclodextrins and regenerating solution), and the micro + ultrafiltration stage, as indicated in Figure 4.

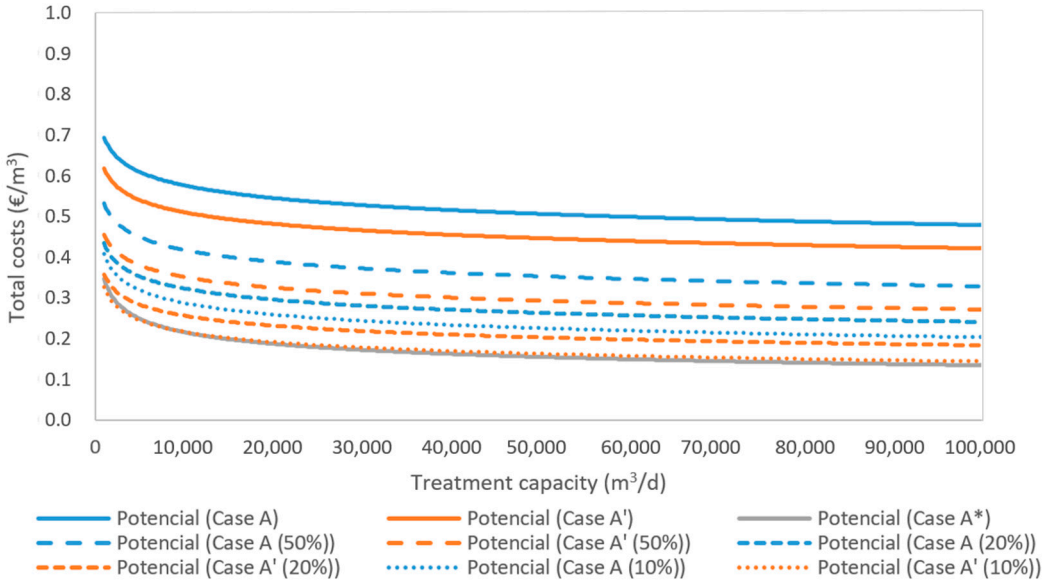


Figure 4. Total costs of Clean Up system and considered alternative for implementation in WWTPs without advanced treatment and discharge of treated water into water bodies.

Considering that the proposed alternative has already been demonstrated and optimized, and is being implemented on a full scale in many WWTPs in Europe, especially in Switzerland, and that, on the other hand, the Clean Up solution is a recent development, and therefore its operating costs could be optimized, a comparative study of costs between both technologies is then considered in which the variation in the costs of the Clean Up system is taken into account as a function of these commented factors, namely, the energy consumption of photocatalysis, acquisition cost of chemicals used in the adsorption stage, and the MF + UF stage. In this way, it is possible to know, for each scenario, the conditions that should exist for the Clean Up solution to be economically competitive compared to the proposed alternative. Thus, the following graphs show, for each of the contemplated scenarios, and depending on the treatment capacity of the facility, the total costs of the Clean Up solution compared to those of the alternatives considered. In the case of Clean-up costs, these are presented as a function of the percentage of reduction in the cost of electricity consumption for photocatalysis and the purchase price of the chemicals used in adsorption–regeneration operations.

Scenario 1: Application in WWTPs without advanced treatment for the removal of suspended solids, which discharge the treated water into water bodies. In this scenario, both the Clean Up system (Cases A and A'), as well as the alternative (Case A*) would be implemented in the WWTP with the aim of limiting the presence of EPs in said water bodies. It is convenient to remember the difference between the two considered cases of the Clean

Up implementation (Case A and A'). While Case A includes a microfiltration followed by an ultrafiltration stage, as an advanced treatment for the elimination of suspended solids, turbidity and pathogenic microorganisms, Case A' includes instead a direct filtration process similar to the one used in the majority of WWTPs that includes advanced treatment, as it is assumed that this treatment is sufficient to give a proper degree of removal of suspended solids. This system is proposed as an alternative to Case A, given the high cost involved in the UF stage. Figure 4 shows the graphs with the total costs calculated and adjusted to a potential relationship in all cases. The dashed lines represent different cases in which it has been assumed that the costs of the factors indicated above are reduced by a certain percentage. For example, the curve "Case A (50%)" represents the costs of applying the Clean Up system, including the MF + UF stage, and in which it has been assumed that both the electrical consumption of the photocatalysis stage and the cost of the chemicals used in the adsorption–regeneration stage is reduced by 50%.

According to the results obtained for this scenario, the Clean Up solution would only be economically competitive not including a UF stage, but rather another direct filtration treatment similar to those used in most WWTPs that have advanced treatment, and if the electricity consumption of the photocatalysis and the acquisition costs of the chemicals of the adsorption–desorption stage were reduced to approximately 10% or less of the costs considered for the calculation of Cases A and A'. This would imply the need to achieve an electrical consumption of 0.17 kWh/m^3 or less, and costs of 0.5 EUR/kg for the CDs and 0.1 EUR/kg for the regenerating solution.

Scenario 2: Application in WWTPs without advanced treatment for removal of suspended solids, which discharge the treated water into water bodies, but intend to reclaim water. In this scenario, both the Clean Up system (Cases B and B'), as well as the alternative (case B*), would be implemented in the WWTP with the aim of limiting the presence of EPs in reclaimed water. Figure 5 includes the graphs with the total costs calculated, and adjusted to a potential relationship in all cases.

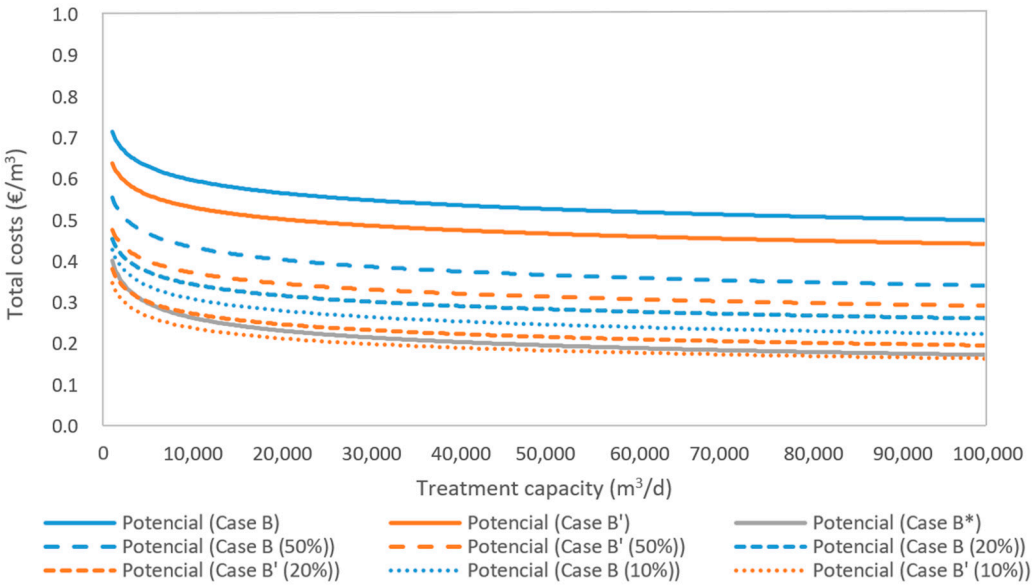


Figure 5. Total costs of Clean Up system and considered alternative for implementation in WWTPs without advanced treatment, which discharge the treated water into water bodies, and which intend to reclaim water.

In this scenario, the Clean Up solution would be economically competitive not including a UF stage, but rather another direct filtration treatment, as in the previous case, and if the electricity consumption of the photocatalysis and the acquisition costs of the chemicals of the adsorption–desorption stage were reduced to approximately 12% or less of the costs considered for the calculation of Cases B and B'. This would imply the need

to achieve an electrical consumption of 0.20 kWh/m^3 or less, and costs of 0.6 EUR/kg for the CDs and 0.12 EUR/kg for the regenerating solution. The results are slightly better for the Clean Up case than in the previous scenario because said system is valid for obtaining reclaimed water, with the simple addition of a final chlorination stage, while with the proposed alternative it would be necessary to apply a final stage of UV disinfection and final chlorination.

Scenario 3: Application in WWTPs that already have an advanced treatment for the removal of suspended solids and the UV disinfection stage, and intend to discharge treated water into water bodies or to reclaim water. In this scenario, both the Clean Up system (Cases C and D'), as well as the alternative (case C* and D*), would be implemented in the WWTP with the aim of limiting the presence of EPs in discharged or reclaimed water. Cases C and C* refer to a situation in which it is intended to discharge the treated water into water bodies, while D and D* are intended to reclaim water. Figure 6 includes the graphs with the total costs calculated, and adjusted to a potential relationship in all cases.

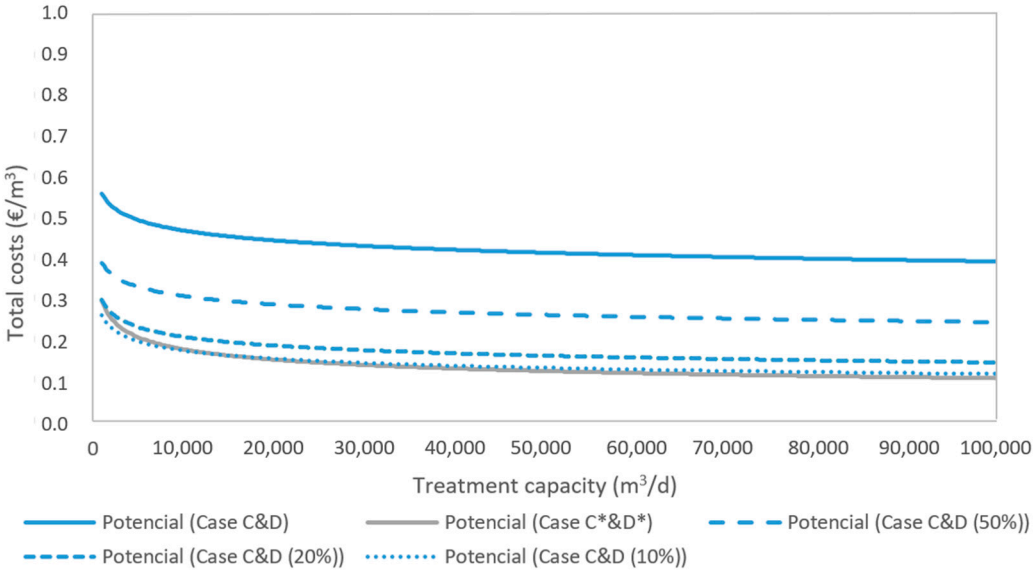


Figure 6. Total costs of Clean Up system and considered alternative for implementation in WWTPs that already have advanced treatment for suspended solids removal and UV disinfection stage and which intend to discharge treated water into water bodies or to reclaim water.

According to the results obtained for this scenario, the Clean Up solution would only be economically competitive if the electricity consumption of the photocatalysis and the acquisition costs of the chemicals of the adsorption–desorption stage were reduced to approximately 10% or less of the costs considered for the calculation of Cases A and A'. Like the first scenario, this would imply the need to achieve an electrical consumption of 0.17 kWh/m^3 or less, and costs of 0.5 EUR/kg for the CDs and 0.1 EUR/kg for the regenerating solution.

4. Conclusions

The present report describes the results of the technical–economic assessment of the Clean Up solution. From a technical point of view, the viability of the Clean Up system is evaluated by being applied as an advanced treatment system for treated urban wastewater, for the elimination of pathogens and emerging pollutants (EPs), considering the established quality criteria by current regulations. In this sense, it is a technology that has been successfully validated at an experimental level, and that offers similar removal performance to those of the most efficient alternatives available on the market.

The technical–economic assessment of the Clean Up solution has been based on the following steps: (i) Estimation of the treatment costs of the Clean Up system, applied at

an industrial level. For said estimation, it has been considered both data obtained in the experimental phase of the project carried out with a pilot plant and general information obtained from various technical bibliographic sources. (ii) Estimation of the treatment costs of the most advantageous technological alternative to the Clean Up system from the technical–economic point of view, applied at an industrial scale, and in the same scenario and conditions as those assumed for the Clean Up system. This alternative is based on an ozonation treatment followed by a biological filtration stage (slow sand filters with biofilm formation in upper layers). It has already been validated at a technical and economical level and is being implemented at an industrial scale in several European countries, as a way to limit the presence of EPs in WWTP effluents. To carry out the estimation, information from industrial facilities that operate in the same application with the aforementioned technology has been taken. (iii) Comparison of the treatment costs of both alternatives, applied in all cases under similar conditions and assuming similar performance. Treatment costs are considered as the sum of operating and capital costs. On the other hand, for the proper comparison of the costs of both technologies, a similar EP removal performance has been assumed in both cases, specifically, yields of EP removal higher than 80% and figures that have been experimentally validated in each case.

Both in the case of the Clean Up solution and the proposed alternative, costs have been estimated for the same application scenarios. Firstly, the treatment capacity of the facility has been considered as a factor influencing costs. Thus, the costs have been estimated for an interval between 1000 and 100,000 m^3/d of treatment capacity. On the other hand, it has also been considered as a factor whether or not the WWTP has a tertiary treatment for the removal of the suspended solids that remain in the secondary effluent, since this stage is necessary for the proper operation of the process, both in the case of the Clean Up system, as in the proposed alternative. Finally, whether the objective of the WWTP is to discharge the treated water into water bodies or to reclaim water for using it in agriculture, has also been considered.

Regarding the obtained results, although the treatment costs of the Clean Up system are competitive and are in line with those of most water reclamation treatments, they are higher than those of the proposed alternative. Specifically, they vary between 0.73 and 0.40 EUR/m^3 depending on the factors indicated in the previous paragraph, while in the case of ozonation + biological filtration, they vary between 0.42 and 0.11 EUR/m^3. Regarding the investment costs, they have been estimated lower in the case of the Clean Up alternative. Specifically, they could vary between 0.19 and 0.05 EUR/m^3, while in the ozonation + biological filtration case, they could vary between 0.23 and 0.06 EUR/m^3, depending on the factors previously pointed out. On the other hand, the operation costs are higher in the case of the Clean Up system (0.54–0.35 EUR/m^3) as compared with the raised alternative (0.19–0.04 EUR/m^3). Focusing the analysis on the operational costs of the Clean Up system, it can be observed that the operational factors with the most influence are the electrical consumption of the photocatalysis stage, the chemicals used in the adsorption stage (cyclodextrins and regenerating solution), and the consumptions associated with the micro + ultrafiltration stage. Considering that the proposed alternative has already been demonstrated and optimized, and is being implemented on a full scale, and that on the other hand, the Clean Up solution is of recent development, and therefore its operating costs could be optimized, a comparative study of costs between both technologies is then considered in which the variation in the costs of the Clean Up system is taken into account as a function of these commented factors.

This analysis has been carried out for each of the considered scenarios in order to determine in each case the conditions that should exist for the Clean Up solution to be economically competitive compared to the proposed alternative. Considering the application in WWTPs without advanced treatment for removal of suspended solids, which currently discharge the treated water into water bodies, the Clean Up solution would only be economically competitive not including a UF stage, but rather another direct filtration treatment similar to those used in most WWTPs that include advanced treatment.

And, if the electricity consumption of the photocatalysis and the acquisition costs of the chemicals of the adsorption–desorption stage were reduced to approximately 10% or less of the costs considered for the cost estimation. This would imply the need to achieve an electrical consumption of 0.17 kWh/m^3 or less, and costs of 0.5 EUR/kg for the CDs and 0.1 EUR/kg for the regenerating solution (sodium chloride, NaCl). On the other hand, considering the application in WWTP without advanced treatment for removal of suspended solids, which currently discharge the treated water into water bodies, but intend to reclaim water, the Clean Up solution would be economically competitive not including a UF stage, but rather another direct filtration treatment, as in the previous case, and if the electricity consumption of the photocatalysis and the acquisition costs of the chemicals of the adsorption–desorption stage were reduced to approximately 12% or less of the costs considered for the cost estimation. This would imply the need to achieve an electrical consumption of 0.20 kWh/m^3 or less, and costs of 0.6 EUR/kg for the CDs and 0.12 EUR/kg for the regenerating solution (NaCl). The results are slightly better for the Clean Up case than in the previous scenario because the said system is valid for obtaining reclaimed water, with the simple addition of a final chlorination stage, for assuring the presence of a residual oxidant in the treated water, while regarding the proposed alternative, it would be necessary to apply a final stage of UV disinfection and final chlorination. Finally, we consider the application in WWTPs, which already have advanced treatment for the removal of suspended solids, and the UV disinfection stage, which intends to discharge treated water into water bodies or to reclaim water. According to the results obtained for this scenario, the Clean Up solution would only be economically competitive if the electricity consumption of the photocatalysis and the acquisition costs of the chemicals of the adsorption–desorption stage were reduced to approximately 10% or less of the costs considered for the cost estimation. Like the first scenario, this would imply the need to achieve an electrical consumption of 0.17 kWh/m^3 or less, and costs of 0.5 EUR/kg for the CDs and 0.1 EUR/kg for the regenerating solution (NaCl).

Bearing in mind that the Clean Up system is designed for tertiary or advanced wastewater treatment, an objective of transferability to other sectors is set as a polishing stage as a way to increase the degree of treatment of the effluents generated in the industrial wastewater treatment plants (IWWTP), thus opening up the possibility for their reuse. Knowing that the difference between the Clean Up system and conventional tertiary treatments is that with the former, it is possible to remove EPs, its application as a polishing stage in the treatment of industrial wastewaters would make sense in those cases in which the IWWTP's effluents to be treated may contain this type of compounds because they have not been efficiently removed in the existing industrial wastewater treatments. Then, the Clean Up system would be applied with the aim of reclaiming water, also avoiding the presence of these pollutants in the reclaimed water. The water treatment industry and the agri-food sector are identified as a potential target for the transfer of Clean Up technology. The agri-food sector's wastewater, similar in quality and quantity to municipal wastewater, necessitates additional treatment stages for effluent discharged directly into water bodies, highlighting the Clean Up technology's efficacy in removing persistent pollutants common in certain agri-food sub-sectors. Moreover, this sector presents a substantial market for wastewater treatment and reclamation, especially for agricultural reuse. Most companies already comply with legal discharge requirements, positioning water reclamation as a feasible advancement. On the other hand, the waste management sector, particularly those managing biodegradable wastewater with potential synthetic pollutants, like chemical toilets, also emerges as a key area for applying Clean Up technology, enhancing water treatment to meet discharge standards into natural water bodies. Due to the treatment flow limitation of the Clean Up system to 1000 m^3/d and the requirement to consider parallel units for scaling up the daily treatment capacity, it is determined that the most suitable scenarios for the commercial implementation of the Clean Up system are in WWTPs with a small flow or in the previously described industries (also typically with small flows), which do not necessitate an excessive number of Clean Up units.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16060814/s1.

Author Contributions: Methodology, J.M.P.; Formal analysis, V.F.; Investigation, V.F.; Data curation, J.M.P.; Writing—original draft, J.M.P.; Writing—review & editing, V.F.; Project administration, V.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission, Grant Agreement LIFE16ENV/ES/000169, "Validation of Adsorbent Materials and Advanced Oxidation Techniques to Remove Emerging Pollutants in Treated Wastewater", Life Clean Up.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors wish to express their gratitude to CETENMA for their collaboration in the execution of economic analyses and to David Campos and Paula Sanchez for their participation in the drafting of this report.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any or financial no-financial aspect that could be construed as a potential conflict of interest.

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