Technical and Economic Assessment of the Fourth Stage of Plovdiv Wastewater Treatment – Calculations, Scenarios and Cost-Effectiveness

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Abstract

This paper assesses the technical and economic feasibility of implementing quaternary (fourth-stage) treatment for micropollutant removal at the Plovdiv wastewater treatment plant (WWTP) located in Bulgaria (378 454 PE design, Q_{avg} 129 047 m^3/d). The cost structure is prepared based on a technical design calculation that takes into account specific dosages of ozone, powdered and granular activated carbon, and on-site PSA generation of oxygen for the ozonation step, tailored to the specific conditions of the plant. Seven scenarios are evaluated with three ozone doses (5, 7, 10 mg O_3/L) followed by a biologically active filter (O_3+BAF), a combined O_3+GAC scheme, GAC stand-alone, and two PAC dosing options (15 mg/L after secondary treatment and 25 mg/L in the bioreactor).

For O_3+BAF, CAPEX is estimated at 16.48 €/PE (6.24 M€). The minimum effective ozone dose (5 mg/L) yields the lowest total annual cost of 2.89 €/PE.y, the typical operating dose (7 mg/L) yields 3.25 €/PE·y. The PAC options are substantially more expensive, reaching 5.62 €/PE·y for dosing after secondary treatment and 7.62 €/PE·y for dosing in the bioreactor. Electricity demand is dominated by ozone production (7.9 GWh/y) and PAC options shift costs towards consumables and sludge handling. The O_3+GAC configuration provides the highest removal performance at intermediate costs (3.25 €/PE.y).

A tornado sensitivity analysis around the 3.25 €/PE·y baseline shows that the recommended O_3+BAF configuration remains below 4.16 €/PE·y under the tested one-at-a-time variations. The analysis confirms that electricity price and ozone dose are the dominant cost drivers. Therefore, the final technology recommendation is interpreted together with the multi-criteria comparison rather than as a purely cost-based ranking. A new six-criterion multi-criteria comparison covering cost, indicative carbon footprint, sludge implications, transformation-product risk, operational risk and sorbent regenerability complements the cost ranking.

The results confirm significant economies of scale at large wastewater treatment plants. The recommended O_3+BAF configuration results in total annual costs of €2.89 - 3.25/PE·year for Plovdiv and a unit cost of €0.026/m^3, which places it below the overall average of the European reference set (€7.3/PE·year).

Novelty. To the best of the author's knowledge, this is the first systematic techno-economic comparison of quaternary-treatment scenarios for a Bulgarian wastewater treatment plant prepared for the peer-reviewed

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literature. It additionally contributes a sensitivity-informed identification of the cost drivers that govern the choice between O_3, PAC and GAC for a large-scale Balkan agglomeration, a setting under-represented in the existing micropollutant-removal literature, in which most studies originate from other countries.

Keywords: granular activated carbon (GAC); micropollutants; ozonation; powdered activated carbon (PAC); wastewater treatment plant (WWTP).

Introduction

European regulatory developments in the field of urban wastewater began with Directive 91/271/EEC, which linked the obligations to build sewerage infrastructure and secondary biological treatment to the size of the agglomeration. This document is the first comprehensive piece of legislation that obliges Member States to systematically build sewerage networks and treatment plants (WWTPs) (Council of the European Communities, 1991; European Commission, 1998, 1999, 2019).

On 27 November 2024 the European Parliament and the Council adopted the recast Directive (EU) 2024/3019 (European Commission, 2024). The main requirements set out in the revised Directive are as follows, with the deadlines shown in Table 1:

1. **Quaternary treatment:** discharges from urban wastewater treatment plants treating a load of 150 000 PE and above must progressively comply with quaternary-treatment requirements by 2033, 2039 and 2045, while additional risk-based obligations apply to discharges from agglomerations of 10 000 PE and above in areas identified as being at risk from micropollutants. The required removal efficiency is at least 80% for the selected indicator substances listed in Annex I, Table 3;
2. **Energy neutrality:** the Directive introduces a national-level energy-neutrality target for urban wastewater treatment plants treating a load of 10 000 PE and above, with interim targets of 20%, 40%, 70% and 100% of annual energy use to be covered by renewable energy by 2030, 2035, 2040 and 2045, respectively. Renewable energy generated on-site or off-site may count towards this target, and a limited share of external non-fossil energy may be used under the conditions set by the Directive.
3. **Monitoring and reporting:** Directive (EU) 2024/3019 strengthens wastewater surveillance, treatment-performance monitoring and pollutant monitoring.
4. **Extended producer responsibility:** producers of pharmaceuticals and cosmetics must contribute to the additional costs of quaternary treatment through extended producer responsibility schemes, covering at least 80 % of the relevant costs.

Table 1
Phased obligations for urban wastewater treatment under the new Directive 2024/3019

Treatment level	Agglomeration	Final (overall) deadline	Intermediate steps/comments
Secondary (biological)	1000 - 2000 PE	31 December 2035	Derogations are possible under strict conditions.
Tertiary (N/P removal)	≥ 150 000 PE and sensitive areas	30% by 2033; 70% by 2036; 100% by 2039	Member States shall publish a list of water bodies sensitive to eutrophication by 31 December 2027.
Tertiary (N/P removal)	≥ 10 000 discharging into sensitive areas	20% by 2033; 40% by 2036; 60% by 2039; 100% by 2045	-
Quaternary (micropollutants)	≥ 150 000 PE	20% by 2033; 60% by 2039; 100% by 2045	For agglomerations of 10000 - 150 000 PE, quaternary treatment is only required when the risk assessment shows a need.
Quaternary (micropollutants)	≥ 10 000 PE discharging into risk areas	10% by 2033; 30% by 2036; 60% by 2039; 100% by 2045	Member States to publish the list of risk areas by 31 December 2030.

For the Plovdiv case, Article 8(1) is the decisive provision because the WWTP treats a load above 150 000 PE.

Bulgaria, Croatia and Romania may benefit from specific derogations for collection and secondary-treatment obligations in smaller agglomerations. These derogations do not apply to the Article 8 quaternary-treatment requirements for large WWTPs.

However, there is no paragraph allowing a postponement of Article 8 quaternary-treatment requirements for urban wastewater treatment plants treating a load of 150 000 PE and above. Unlike Articles 3 (collection), 6 (secondary) and 7 (tertiary), where Bulgaria, Croatia and Romania receive an additional 12-14 years only for small and medium-sized agglomerations, in Article 8 (requirements for quaternary treatment) there is no such postponement.

To meet these obligations, most European countries have followed a sequence of laboratory experiments, pilot installations and full-scale implementation. After more than a decade of such studies, three families of solutions have emerged as practically dominant for municipal applications (Table 2):

- ozonation (with downstream biological post-treatment);
- adsorption with powdered activated carbon (PAC);
- adsorption with granular activated carbon (GAC).

Other techniques – membrane filtration (UF/NF/RO), advanced oxidation processes coupled to UV or catalysts, photolysis, ultrasound and combined physico-chemical schemes have been investigated but are not consistently competitive at full scale once removal efficiency, costs and operational complexity are jointly considered (Mulder et al., 2015; Pistocchi et al., 2022; Sturm et al., 2022; Joller & Hug, 2024).

Table 2
Main methods for quaternary wastewater treatment

Principle of operation	Strengths	Limitations/risks
Ozonation (treatment efficiency ≥ 80% with subsequent filtration)		
Ozone (a strong oxidant) is generated on site and injected into the water with a contact time of 10-20 min. Ozone destroys the molecules of many organic micropollutants or transforms them into more easily biodegradable compounds. (EPA, 2006; VSA Micropoll Platform, n.d.)	Compact equipment, no need to add reagents; low carbon footprint; no sludge formation	Risk of bromate formation – a carcinogenic product; control and/or subsequent biofilter required; Ozone is a toxic gas, which requires strict safety techniques (Sauter, 2024)
Powdered activated carbon (PAC) (treatment efficiency 70-90% depending on the dose)		
Fine carbon (5–35 µm) is dosed into the treated water or directly into the biological step. Pollutants are adsorbed onto the porous surface, after which the carbon is separated with the sludge. (Stapf, 2020)	Lowest initial CAPEX (initial capital expenditure) – only silo and dosing pumps; Flexible, easy to implement in stages	High ongoing OPEX (operating expenses) – single use of carbon; Increases sludge quantities and may require stricter sludge management, potentially thermal treatment depending on contaminant loading and final waste classification; Largest CO_2 footprint (carbon production and combustion)
Granular activated carbon (GAC) (treatment efficiency 80-95%)		
Water passes through a layer of granules (0.6-2 mm) on which micro-pollutants are adsorbed. When capacity drops, the carbon is thermally regenerated and returned to service. (Elavarthi, 2021; PDH-Pro, 2018; U.S. Environmental Protection Agency, 2000)	High and consistent efficiency; retains microplastics/particles; carbon is reactivated, resulting in lower long-term CO_2 and OPEX than PAC	Highest CAPEX (large filter cells, washing system); Requires access to a reactivation furnace; Pre-filtration is necessary due to the risk of clogging the pores of the GAC

Although the techno-economic literature on quaternary treatment has developed substantially over the past decade with consolidated cost relationships, parametric envelopes and operational guidance provided by Pistocchi et al. (2022), Mulder et al. (2015), Joller and Hug (2024), Sauter (2024) and Stapf et al. (2020), among others, the geographic coverage of the published full-scale evidence base is uneven. Comparable assessments concentrate on Western and Central European catchments (Germany, Switzerland, the Netherlands, Austria). To the best of the author's knowledge, no peer-reviewed techno-economic assessment of quaternary treatment under Bulgarian operating and price conditions has been published to date, even though Article 8(1) of the recast Directive (EU) 2024/3019 binds approximately three to five Bulgarian agglomerations in the ≥ 150 000 PE class (Sofia, Plovdiv, Varna, Burgas and Ruse), to implement quaternary treatment between 2033 and 2045, without national derogation.

The present study therefore aims to provide the first such assessment for a Bulgarian WWTP, taking the Plovdiv plant as a representative large-scale case. In doing so, the study (i) re-derives the costs using 2025 EU and Bulgarian unit prices; (ii) documents how the cost ranking of the three principal technologies shifts under the specific combination of conditions characteristic of the Bulgarian setting – the absence of a domestic granular activated carbon reactivation infrastructure, warmer wastewater temperature; and (iii) couples the cost ranking with a six-criterion comparison and a sensitivity analysis, so that the result is reported together with the envelope of input assumptions on which it depends. The methodological pipeline is intentionally documented in a form that can be re-applied directly to the remaining Bulgarian agglomerations and, by extension, to comparable Romanian and Croatian plants subject to the same unconditional regulatory deadline.

Methods

The second largest wastewater treatment plant in Bulgaria, WWTP Plovdiv, serves 378 454 PE. The average daily design flow is 129 047 m^3/d, and the actual organic load at the inlet is 255 944 PE. The plant discharges the treated water into the Maritsa River, a river with a significant base flow, which allows dilution but does not eliminate the risk of micro-pollutant accumulation downstream.

The existing technological scheme includes primary mechanical treatment, a biological stage with aerobic nitrification/anoxic denitrification, secondary radial clarifiers, anaerobic digestion of sludge with cogeneration. However, the treatment technology designed in this way does not include a specific barrier for the treatment of organic micropollutants, which are discharged untreated into the Maritsa River. At present, the Plovdiv WWTP is operating stably after the completed modernisation and is achieving the emission limits for nitrogen and phosphorus with a high environmental effect. The upcoming challenges are related to sludge management and preparation for a future "fourth stage" of treatment in line with the latest European requirements.

The cost estimate for the quaternary treatment of the Plovdiv WWTP is based on the engineering design of the seven treatment scenarios at the plant's actual flow rate (Q_{avg} = 129,047 m^3/day). Ozone doses are expressed as mg O_3 per mg of dissolved organic carbon (DOC) in the wastewater. Three specific doses are evaluated - 0.5, 0.7, and 1.0 mg O_3/mg DOC, corresponding to 5, 7, and 10 mg O_3/L. PAC dosages are assumed to be 15 mg/L for dosing in a separate reactor after secondary sedimentation and 25 mg/L for dosing in the bioreactor (where competition with biomass requires a higher dose). These dose ranges are consistent with pilot-scale evidence from the Lausanne WWTP, where an ozone dose of 5.7 mg O_3/L or PAC doses of 10–20 mg/L achieved an average micropollutant removal of more than 80% relative to raw wastewater (Margot et al., 2013). The standalone GAC configuration is hydraulically sized for an empty bed contact time (EBCT) of 30 minutes, corresponding to a filter bed volume of 2,700 m^3. For the preliminary economic assessment, a GAC quantity of 729 t is adopted as a simplified costing assumption for initial media loading and annual reactivation. The actual GAC inventory and reactivation requirements should be verified during detailed design, considering the selected media properties and site-specific breakthrough characteristics. The

combined O_3+GAC scheme uses half the ozone dose (0.3 mg O_3/mg DOC = 3 mg/L) and 50% of the GAC mass compared to the standalone configuration, reflecting the role of GAC in post-treatment following partial ozonation. The volume of the tanks for the ozone contactor (1,500 m^3, HRT = 15 min) and the PAC contactor (5,377 m^3, HRT = 60 min) is calculated in a similar manner based on the design flow rate. (EPA, 2006; Sauter, 2024; VSA Micropoll Platform, n.d.)

The methodology used here proceeds in five explicit steps:

Step 1. Selection of reference treatment plants and harmonization of input data. Ten preliminary studies covering 40,000 - 1,200,000 PE were used for the analysis. For each plant, the design PE, average daily flow, design peak flow for the 4th stage, and at least one scenario with calculated costs were extracted.

Step 2. Volumetric sizing of the seven Plovdiv scenarios. Three ozone doses (0.5, 0.7, 1.0 mg O_3/mg DOC, equivalent to 5, 7, 10 mg O_3/L) are dimensioned with HRT = 15 min in the ozone contactor. Combined O_3+GAC scheme uses 0.3 mg O_3/mg DOC (3 mg/L) with GAC post treatment at 50 % of the GAC mass of the stand-alone configuration. GAC stand-alone is sized for 2 700 m^3 (EBCT = 30 min), with 729 t/y of GAC adopted as a simplified costing assumption for annual reactivation and two PAC scenarios at 15 mg/L (after secondary settling, HRT = 60 min) and 25 mg/L (dosed into the bioreactor).

Step 3. Cost stack based on 2024–2025 EU and Bulgarian unit prices. Electricity at €0.094/kWh (IBEX baseload April 2025 plus medium-voltage distribution charge; IBEX, 2025), PAC at €1.90/kg, GAC at €1.90/kg for new production and €0.76/kg for reactivation (40% of new production), ozone generator at 12.5 kWh/kg O_3, on-site PSA O_2 generation at 0.4 kWh/Nm^3 O_2, uniform 30-year asset life and a real discount rate of 3% (CRF = 0.0510), 3% maintenance and transport/sludge-handling 0.10 M€/y for GAC and PAC scenarios.

Step 4. Independent cross-check of the obtained unit costs against (a) the PE-based relationship proposed by Pistocchi et al. (2022, Equation 1) and (b) the empirical boundary of the ten reference plants. The design point for Plovdiv is positioned in the resulting €/m^3 - PE space.

Step 5. Sensitivity analysis. The four parameters with the greatest expected impact - electricity price, ozone dose, discount rate and CAPEX deviation are varied one by one around the baseline level, and the resulting tornado diagram is presented in Fig. 3.

The reference dataset comprises ten European WWTP cases, dominated by German feasibility studies and complemented by one Austrian case and one large-scale reference plant for which detailed feasibility studies and costed scenarios are available (Wastewater treatment plant of the city of Niederkassel, 2020; Kommunalbetriebe Emmerich am Rhein, 2013/2014; LANUV NRW, 2020a, 2020b, 2021, 2022; Lugitsch & Partner ZT GmbH, 2022; PFI Planungsgemeinschaft, 2019; Stadt Ibbenbüren, 2019; TUTTAHS & MEYER Ingenieurgesellschaft mbH, 2019). The studies use a unified European cost-reporting framework, allowing direct comparison of CAPEX (in M€ and €/PE) and OPEX (electricity, reagents, labour, sludge handling) across plants spanning two orders of magnitude in PE. The fifty-five individual scenarios available across the ten plants form the empirical envelope against which the Plovdiv estimate is benchmarked in the Results section.

The set of reference data used here is derived from a series of studies conducted in Europe. Four specific points have been explicitly examined to support the relocation to Plovdiv:

- **The footprint of micropollutants in the inflow.** In the majority of the studies, carbamazepine, diclofenac, benzotriazole, and metoprolol predominate, which is consistent with the list of indicators in Annex I, Table 3 of Directive (EU) 2024/3019. Routine monitoring of these substances at the WWTP inlet in Bulgaria is still in its early stages, which is noted as a residual uncertainty and as an element for the pre-design monitoring campaign in Plovdiv.
- **Wastewater temperature.** The average annual inflow temperature in Plovdiv (17–19 °C) is higher than that at the monitored treatment plants in Western Europe. This slightly improves

the kinetics of biological treatment following the ozonation stage (Sauter, 2024) and, by a conservative estimate, has not been accounted for in the present cost assessment.

- **Background level of bromide.** Bromide has not yet been systematically measured in Plovdiv. Since bromide is the main factor in the formation of bromate during ozonation, it is identified as a residual risk that must be characterized during the pre-design phase, and the recommendation in the Discussion section has been clarified accordingly.
- **Difference in electricity prices.** The Bulgarian industrial electricity price used here (0.094 €/kWh, IBEX baseload April 2025 plus medium-voltage distribution charge; IBEX, 2025) is materially below the German non-household equivalent. Eurostat (2025) reports non-household medium-consumer prices in the second half of 2024 of approximately 0.11 €/kWh for Bulgaria and 0.20 €/kWh for Germany (incl. taxes and levies), against an EU average of 0.19 €/kWh, confirming the direction of the price differential at any consumption band. The sensitivity analysis presented in Fig. 3 quantifies how much of Plovdiv's cost advantage is attributable to this difference.

The cost assessment for the Plovdiv WWTP is conducted in two separate stages. First, the CAPEX and OPEX for the seven scenarios are calculated based on local design parameters and unit prices for 2024–2025, as set out in Tables 4 and 5. Second, the resulting unit costs are compared with two independent reference sources - the cost–PE relationship proposed by Pistocchi et al. (2022) on the one hand, and the empirical range of the ten European reference treatment plants summarised on the other. In this way, the estimate for Plovdiv is compared with two reference sources that have been derived independently of one another.

Results

This section summarises feasibility-study data for ten European reference WWTPs, dominated by German cases, used to assess and benchmark the implementation options for the Plovdiv WWTP (Table 3). The documents have been developed using a unified methodology and serve as a pre-project basis for the selection of a technological solution, dimensioning and cost forecasting.

Table 3

European reference WWTPs with considered options for quaternary treatment

WWTP/Location	PE	Qavg.d. (m^3/d)	Q for 4th stage (m^3/h)	Total [€/m^3]	Total [€/PE.y]
WWTP-01	40 000	14 000	940	0.084	10.79
WWTP-02	47 000	6 834	720	0.12	6.16
WWTP-03	48 000	8 588	960	0.23	15.05
WWTP-04	56 000	11 230	1721	0.14	9.92
WWTP-05	64 000	6 452	400	0.15	5.46
WWTP-06	87 000	12 590	400	0.09	4.62
WWTP-07	85 000	13 130	700	0.10	5.50
WWTP-08	88 000	13 186	930	0.22	12.32
WWTP-09	195 000	15 182	800	0.08	2.23
WWTP-10	1 200 000	180 000	8 000	0.021	1.12

For each plant, a complete survey of the initial conditions was carried out, including an inventory of the existing infrastructure and technological scheme, determination of the capacity in population equivalent and the actual hydraulic load, analysis of the receiving water body and the regulatory context (water body class, water protection zones, share of treated water in the effluent), and assessment of operational behaviour in dry and rainy weather.

Water quantity and micro-pollutant load are characterised through targeted monitoring campaigns and/or analysis of available data. Typically, 10-30 indicator compounds are studied, determining the choice and dosage of processes. In cases of planned ozonation, additional requirements for

biological treatment after ozone are also considered. For activated carbon options, adsorption isotherms and the expected efficiency of the treated flow are assessed, as well as the logistics and management of activated carbon (powdered or granulated).

In summary, studies show that for medium-scale plants, ozonation and PAC solutions achieve similar and low specific total costs, while GAC and complex hybrids are more resource-intensive but provide additional security for sensitive receptors.

The calculations per equivalent inhabitant show a mean value of 7.32 €/PE·year, with an interquartile range of 4.83–10.57 €/PE·year. The lowest unit values were observed in WWTP-10 (ozone and sand filtration - 0.021 €/m^3) and the highest at WWTP-3 (ozone + GAC - 0.23 €/m^3) and in some hybrid schemes in WWTP-8 (0.22 €/m^3).

Summarised at the observed scale, the configurations with ozone and PAC, including biological pretreatment, form the lower range of specific total costs, varying on average around 0.12–0.13 €/m^3, while the solutions with GAC as the leading step and the complex hybrids are grouped at higher levels.

The economic part of the assessment is based on the publication by Pistocchi et al. (2022), where, by processing data from multiple European stations, an empirical relationship for the annual costs (sum of investment and operating costs) for quaternary treatment is derived:

$$C_{adv} = 1000 \times PE^{-0.45} \quad (1)$$

Where: C_{adv} - total cost in Euro/inhabitant/year; PE – equivalent number of inhabitants.

The main source for parameterisation of the processes and cost benchmarks studied for the Plovdiv WWTP is based on the studies by Pistocchi et al. (2022), which synthesise the EU experience in quaternary treatment with ozonation and activated carbon (PAC/GAC). This study specifies typical design parameters (contact times, dosing intervals, unit energy costs) and provides an estimate of the total annual cost of quaternary treatment as a function of the scale of the plant (**Eq. 1**), which is also used in this article to verify the plausibility of the results obtained. The same source also systematises ranges by technology (ozone, PAC, GAC and hybrids) in €/m^3 and €/PE·year for different capacities, as well as energy components. These dependencies and assumptions are accepted as a reference framework for the assessment made for the Plovdiv WWTP.

The total annual cost for quaternary treatment is calculated as the sum of investment and operating costs, which are expressed both in €/m^3 (division of the annual volume at the actual Qavg) and in €/PE·year. To verify the plausibility of the forecast in €/PE.year for the Plovdiv WWTP, the function proposed by Pistocchi et al. (2022), **Eq. 1**, is also used, which gives a benchmark of 3.09 €/PE.year for a capacity of 378 454 PE. The value obtained in the present study for the recommended O_3+BAF configuration at the typical operating dose (7 mg O_3/L) is 3.25 €/PE·y. The PAC configurations in **Table 5** are excluded from the calculation of the average value in €/PE·year due to the excessively high operating costs for this scale of plant.

This cross-check allows the Plovdiv scenarios for quaternary treatment to be positioned in a European context and to validate whether the unit costs obtained are within the expected ranges for the scale and technology.

The transfer to local conditions was performed by replacing the technological and cost parameters adopted by Pistocchi et al. with the actual input parameters for Plovdiv. Design capacity of 378 454 PE, Qavg = 129 047 m^3/d, Bulgarian electricity price, and 2025 activated-carbon prices. For ozonation, the annual electricity demand was calculated as the sum of ozone-generator electricity demand, PSA/VPSA oxygen-production electricity demand and auxiliary pumping. No purchased liquid-oxygen cost was applied in the base-case calculation. For PAC, doses of 15 g/m^3 after secondary treatment and 25 g/m^3 in the bioreactor were used. For GAC, the stand-alone configuration

assumes annual reactivation of 729 t/y, with a 5% make-up of virgin GAC after reactivation; the O_3+GAC configuration uses 50% of the stand-alone GAC mass. Additional costs of 0.10 M€/y is included for GAC transport/reactivation logistics and PAC sludge-handling where applicable. It should be interpreted as a preliminary operational allowance rather than as a site-specific service tariff. (Elavarthi, 2021; PDH-Pro, 2018; U.S. EPA, 2000).

The breakdown of costs is summarized in **Table 5** (CAPEX in millions of euros and euros/PE, OPEX broken down by electricity, reagents, oxygen, maintenance, total annual costs in euros/PE·year and euros/m^3). Additional costs for transporting the saturated activated carbon to the reactivation furnace and returning the reactivated carbon are included. For ozonation, the annual electricity demand was calculated as the sum of three components: ozone-generator electricity demand, PSA/VPSA oxygen-production electricity demand, and auxiliary pumping. The ozone generator was assumed to consume 12.5 kWh/kg O_3. Oxygen was assumed to be produced on site by PSA/VPSA, using 0.4 kWh/Nm^3 O_2; at an assumed 10% O_3 concentration in the oxygen gas and 1 Nm^3 O_2 = 1.43 kg, this is equivalent to approximately 2.8 kWh/kg O_3. No liquid-oxygen purchase cost was included in the base-case calculation.

Table 4

Operational and technicaleconomic parameters for the Plovdiv WWTP after technological dimensioning

No	PARAMETER	VALUE	DIMENSION
1	Equivalent inhabitants WWTP	378 454	PE
2	Hydraulic load WWTP	129 047	m^3/d
3	Price of electricity[1]	0.094	€/kWh
4	PAC price[2]	1.90	€/kg
5	Price of GAC regeneration[2]	0.76	€/kg
6	Price of new GAC (refill)[2]	1.90	€/kg
7	Liquid oxygen price (not used in PSA base case)[3]	0.20	€/kg
8	Specific electricity demand of ozone generator using oxygen feed gas	12.50	kWh/kg O_3
9	Specific electricity demand of PSA/VPSA oxygen production	0.40	kWh/Nm^3 O_2
9a	Equivalent PSA/VPSA electricity demand at 10% O_3 in oxygen gas	2.80	kWh/kg O_3
10	Pumps/other (PAC)	0.05	kWh/m^3
11	Pumps/other (GAC)	0.04	kWh/m^3
12	Pumps/other (O_3)	0.06	kWh/m^3
13	GAC regeneration	729	t
14	PAC dose, when dosing after secondary clarifier	15.00	g/m^3
15	PAC dose, when dosing in biological step	25.00	g/m^3
16	Volume of GAC tank	2700.00	m^3
17	PAC tank volume	5377.00	m^3
18	Ozone tank volume	1500.00	m^3
19	Investment for contact tank	500.00	€/m^3
20	Investment for sand filter	8.00	€/PE
21	Investments for ozone installation	6.50	€/PE
22	3% maintenance	0.45	€/PE.a
23	Transport/reactivation and sludge-handling allowance for GAC/PAC	0.10	million €/a

1. The price of electricity is calculated as 0.0850 €/kWh + 0.0090 €/kWh = 0.094 €/kWh, where 0.0850 €/kWh is the average day-ahead base-load price on IBEX for April 2025, and 0.0090 €/kWh is the charge for transmission through the medium-voltage distribution network.

2. The price of activated carbon in 2025 is €1.90/kg (Business Analytiq, 2025).
3. In the base-case calculation, oxygen is assumed to be produced on site by PSA. Therefore, no separate purchased liquid-oxygen cost is applied in **Table 5**. Oxygen-related costs are represented through the electricity demand of the PSA system. The liquid oxygen price in **Table 4** is retained only as an alternative-scenario parameter and is not used in the base-case cost calculation.
4. The PSA/VPSA electricity demand is calculated as 0.4 kWh/Nm^3 O_2. Assuming 10% O_3 in the oxygen gas and 1 Nm^3 O_2 = 1.43 kg, this corresponds to approximately 2.8 kWh/kg O_3. Therefore, no separate liquid oxygen purchase cost is applied in the base-case calculation.

Table 5

Technical and economic assessment of investment and operating costs for Plovdiv WWTP for different treatment technologies

TREATMENT TECHNOLOGY	COSTS FOR OZONE INSTALLATION					GAC COSTS		PAC COSTS	
	O_3 (kg/PE·y)	O_3 mass per year, (kg O_3/y)	Energy for O_3 generator, (GWh/y)	Energy for O_2 production (GWh/y)	Cost for pure oxygen, (million €/y)	GAC regeneration, (million €/y)	Price for new GAC replacement (million €/y)	Mass of PAC (t/y)	Price for PAC dosing, (million €/y)
$O_3$1 (0.5 mgO_3/mg DOC)	0.622	235511.15	2.94	0.66	0.00				
$O_3$2 (1.0 mg O_3/mg DOC)	1.245	471022.30	5.89	1.32	0.00				
$O_3$3 (0.7 mg O_3/mg DOC)	0.871	329715.61	4.12	0.92	0.00				
O_3+GAC (0.3 mgO_3/mg DOC)	0.373	141306.69	1.77	0.40	0.00	0.277	0.035		
GAC (standalone)						0.554	0.069		
PAC1 (15 mg PAC/l)								706.53	1.34
PAC2 (25 mg PAC/l)								1177.56	2.24

TREATMENT TECHNOLOGY	ELECTRICITY COSTS			OPERATING		CAPITAL INVESTMENTS				TOTAL COSTS	
	Pumps, etc. GWh/y	Total Electricity, (GWh/y)	Electricity costs (million €/y)	OPEX (million €/y)	OPEX (€/PE·y)	$CAPEX_0$ (€/PE)	$CAPEX_0$ (million €)	CAPEXa (million €/y)	CAPEXa (€/PE·y)	TOTAL (million €/y)	TOTAL (€/PE·y)
$O_3$1 (0.5 mgO_3/mg DOC)	2.83	6.43	0.60	0.78	2.05	16.48	6.24	0.32	0.84	1.09	2.89
$O_3$2 (1.0 mg O_3/mg DOC)	2.83	10.03	0.94	1.11	2.95	16.48	6.24	0.32	0.84	1.43	3.79
$O_3$3 (0.7 mg O_3/mg DOC)	2.83	7.87	0.74	0.91	2.41	16.48	6.24	0.32	0.84	1.23	3.25
O_3+GAC (0.3 mgO_3/mg DOC)	1.88	4.05	0.38	0.96	2.55	13.88	5.25	0.27	0.71	1.23	3.25
GAC (standalone)	1.88	1.88	0.18	1.07	2.83	7.23	2.74	0.14	0.37	1.21	3.20
PAC1 (15 mg PAC/l)	2.36	2.36	0.22	1.84	4.85	15.10	5.72	0.29	0.77	2.13	5.62
PAC2 (25 mg PAC/l)	2.36	2.36	0.22	2.73	7.22	8.000	3.03	0.15	0.41	2.89	7.62
Operating costs (€/m3) 0.029						Total costs (€/m^3) 0.107				Average 3.28	
									$C_{adv} = 1000 \times PE^{-0.45}$		3.09

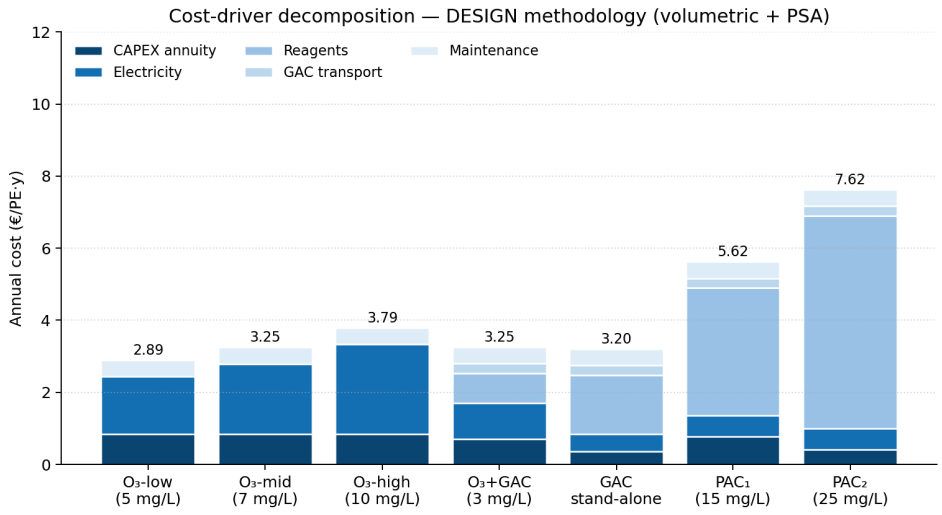
Discussion

The Plovdiv wastewater treatment plant treats an average of 129 047 m^3/d of wastewater generated by approximately 378 454 population equivalents (PE). Considering the revised Urban Wastewater Directive (European Commission, 2024), which introduces a phased minimum reduction of priority micro-pollutants by at least 80%, the plant needs a fourth stage of treatment. Three established technologies have been costed: (1) ozonation with a biologically active sand filter (O_3 + BAF), (2) ozonation combined with granular activated carbon filters (O_3 + GAC) and (3) dosing of powdered activated carbon (PAC).

For the Plovdiv WWTP, ozonation combined with a biologically active filter (O_3+BAF) at the typical operating dose of 7 mg O_3/L emerges as the recommended option, with a total annual cost of 3.25 €/PE·y. The low-dose variant of 5 mg O_3/L gives the lowest nominal cost of 2.89 €/PE·y and may be suitable during periods with lower influent loading, while the high-dose variant of 10 mg O_3/L reaches 3.79 €/PE·y. The combined O_3+GAC scheme is cost-comparable at 3.25 €/PE·y and stand-alone GAC remains slightly lower in nominal terms at 3.20 €/PE·y. However, both GAC-containing configurations depend on reliable access to external or regional reactivation infrastructure. Until such infrastructure becomes operational in Bulgaria or in a nearby regional setting, O_3+BAF remains the practically preferred short- to medium-term option. PAC dosing in either configuration is considerably more expensive (5.62 – 7.62 €/PE·y), driven by recurring reagent consumption at 706.5 to 1 177.6 t PAC/y, and should be considered only as a temporary or emergency solution.

Fig. 1

Cost-driver decomposition for the seven Plovdiv WWTP quaternary-treatment scenarios. CAPEX annuity at i = 3 %, n = 30 y. Numbers above the bars are total annual cost in €/PE·y.



First, the three O_3+BAF variants share an identical CAPEX annuity (0.84 €/PE·y) and differ only in their electricity component, which rises from 1.60 to 2.49 €/PE·y between the low and high doses. Operational electricity bill is therefore the principal lever for ozonation at the Plovdiv scale, with on-site PSA O_2 generation accounting for 12 % of the ozone-related electricity. Second, the PAC scenarios are dominated by the recurring reagent cost (3.55 €/PE·y for PAC_1 at 15 mg/L and 5.91 €/PE·y for PAC_2 at 25 mg/L), which alone exceeds the total annual cost of all O_3-based options. Third, GAC stand-alone exhibits a low CAPEX annuity (0.37 €/PE·y) and a comparatively high reagent component (1.65 €/PE·y, dominated by reactivation at 0.76 €/kg for 729 t/y). This nominal advantage is structurally conditional on regular access to a reactivation furnace, which is currently located approximately 1 000 km from Plovdiv (Pischelsdorf, Austria; Donau Carbon GmbH, 2025).

The decomposition therefore clarifies that the choice between the three technology families is governed by different cost drivers – electricity for ozonation, reagent for PAC, and reactivation logistics for GAC – and that the recommendation derived in the Discussion section depends on which of these drivers is most exposed to upward movement under local conditions.

Fig. 2 shows the lowest reported total costs (€/m^3) for each reference wastewater treatment plant listed in Table 3, plotted on a logarithmic scale according to its design capacity (PE), along with the calculations made for Plovdiv (O_3+BAF at a typical operating dose of 7 mg/L = 0.026 €/m^3). A power-law fit on the ten reference plants yields costs = 59 · PE^(–0.55), reflecting the significant economies of scale that determine the costs of quaternary treatment across a range of two orders of magnitude in plant size. The estimate for Plovdiv lies below the fitted curve, which predicts 0.048 €/m^3 at 378 454 PE, and within the range spanned by the reference plants of comparable and larger scale. This positioning indicates that the recommended O_3+BAF configuration delivers a unit cost at the favourable edge of the European full-scale evidence for plants of comparable scale, consistent with the lower Bulgarian electricity price, and confirms that the technological-dimensioning approach used here produces results aligned with the operating experience of the reference plants.

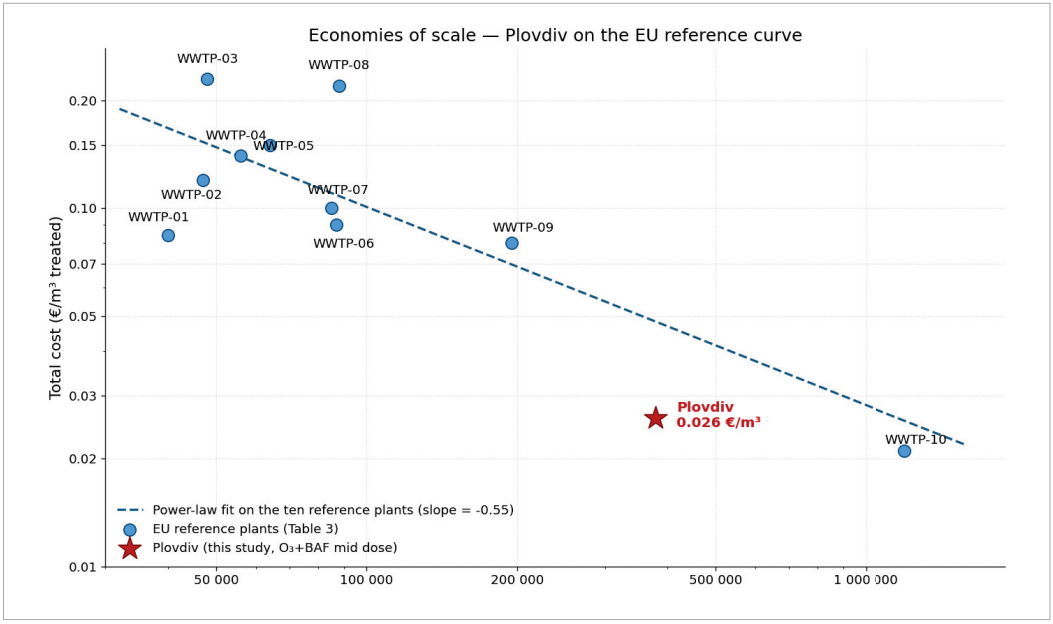


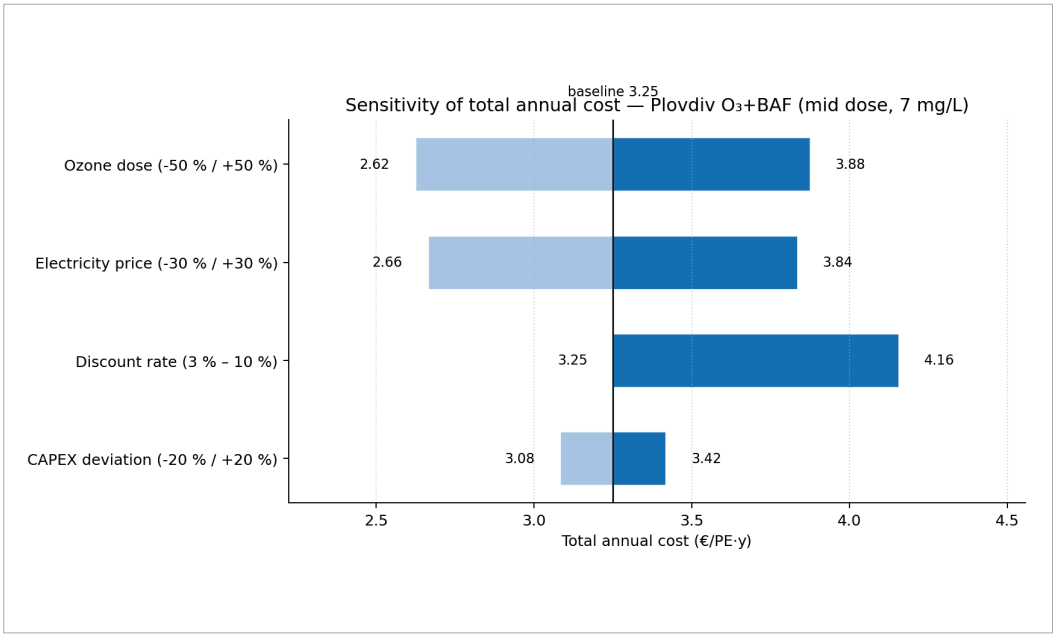
Fig. 2
Economies of scale - lowest reported total cost per m^3 versus design PE for the ten EU reference plants and Plovdiv.

The sensitivity of the recommended O_3+BAF mid-dose configuration (7 mg/L, baseline 3.25 €/PE·y) to the four highest-leverage parameters is summarised in Fig. 3 (tornado). The ozone dose (±50 %) and the electricity price (±30 %) generate the widest envelopes of similar magnitude (2.62 – 3.88 €/PE·y and 2.66 – 3.84 €/PE·y, respectively), reflecting the fact that ozone generation and on-site PSA O_2 supply together account for 69 % of the total electricity demand. The discount rate is the second one-sided lever - moving from 3 % to 10 % raises the total annual cost from 3.25 to 4.16 €/PE·y. CAPEX deviation has the smallest leverage (3.08 – 3.42 €/PE·y for a ±20 % CAPEX deviation, i.e. ±5 % around the baseline total). Even at the upper edge of every excursion the recommended option remains below 4.16 €/PE·y, which is below the average of the EU reference set (7.3 €/PE·y), confirming that the recommendation is robust under the sensitivity envelope tested.

From the comparison illustrated above, the graphs also suggest priorities for risk management in quaternary treatment. For ozonation, energy efficiency and control of additional “harmful” parameters (presence of NO_2-N, Br^-) are key, as they directly affect operating costs and the need

Fig. 3

Tornado sensitivity of the total annual cost of the recommended O_3+BAF (mid-dose) configuration to one-at-a-time variation of four input parameters around the baseline of 3.25 €/PE·y.



for additional treatment. For the PAC approach, the focus is on carbon logistics and subsequent sludge disposal, while for GAC it is on the reactivation strategy and useful life of the filters. Plovdiv's ranking among the European wastewater treatment plants of similar size examined along both axes (€/m^3 and €/PE·year) shows that, at the selected scale and technological integration, ozone is an economically sustainable choice, provided that the quality prerequisites (pre-filtration/additional treatment, nitrite and bromide control) are strictly maintained and the expected energy optimisation of the system is achieved.

Multi-criteria comparison

The cost ranking is necessary but not sufficient. Recent literature emphasises that the choice between ozonation, PAC and GAC is co-determined by operational and environmental dimensions that a cost-only comparison cannot capture (Sauter, 2024; Stapf et al., 2020). A six-criterion comparison is therefore added, covering total annual cost, indicative carbon footprint, sludge implications, transformation-product risk, operational risk, and sorbent regenerability. The rows for cost per m^3 and for the sensitivity envelope in **Table 6** detail the cost criterion. The row on compatibility with the energy-neutrality pathway under Article 11 of Directive (EU) 2024/3019 is provided as supplementary information only; it is not counted as a seventh criterion and does not affect the overall qualitative score, because all four options are rated equally (High). The carbon-footprint indicator is computed from the modelled electricity and reagent demands. For ozonation, oxygen-related emissions are represented through the electricity demand of the PSA system. Reagent-related emission factors are applied to PAC production, GAC replacement and GAC reactivation. On this basis the indicative carbon footprint ranges from approximately 0.030 kg CO_2eq/m^3 for GAC stand-alone and 0.062 kg CO_2eq/m^3 for O_3+BAF (mid dose) to 0.146 kg CO_2eq/m^3 for PAC after secondary, approximately 2.4 times the value of the recommended ozonation option.

Because PAC and GAC scenarios are strongly controlled by reagent economics, an additional screening sensitivity was considered for activated-carbon price and GAC reactivation cost. A ±30% variation in PAC/GAC unit costs does not change the rejection of PAC as a near-term base-case option and reinforces that their selection remains conditional on reliable reactivation logistics. This supports the recommendation of O_3+BAF not as the universally cheapest technology, but as the most robust near-term option under current Bulgarian infrastructure conditions.

Table 6
Multi-criteria comparison of the four technologies for the Plovdiv WWTP.

Criterion	O_3+BAF (mid, 7 mg/L)	O_3+GAC (3 mg/L)	GAC stand-alone	PAC after secondary
Total annual cost (€/PE·y)	3.25	3.25	3.20	5.62
Total annual cost (€/m^3)	0.026	0.026	0.026	0.045
Sensitivity envelope (€/PE·y)	2.62 – 4.16	2.76–3.74	2.56–3.84	4.4 – 7.0
Indicative carbon footprint (kg CO_2eq/m^3)	0.062	0.040	0.030	0.146
Sludge implications	No additional sludge from the step	Marginal (rinse water of GAC)	No additional sludge	Sludge quantities increase by more than 10% and may require stricter sludge management
Transformation-product / by-product risk	Bromate risk if Br^- > 100 µg/L; mitigated by BAF	Bromate risk reduced (half ozone dose), polished by GAC	Very low	Very low
Operational risk	Medium (O_2 PSA, ozone safety, BAF maintenance)	Medium-high (both routines)	High (foreign reactivation until regional furnace exists)	Low (silo + dosing pumps)
Sorbent regenerability	n/a	Yes (every 12 months)	Yes (every 12 months)	No (single use)
Supplementary information (not scored): Compatibility with energy-neutrality pathway under Article 11 of Directive (EU) 2024/3019	High	High	High	High
Overall qualitative score	+ (recommended, short / medium term)	+ (recommended once regional GAC reactivation exists)	± (cost-attractive but operationally exposed)	– (temporary / emergency option)

Implementation pathway and financing

Article 8(1) of Directive (EU) 2024/3019 binds Plovdiv to the 2033/2039/2045 phasing without national derogation. A pragmatic implementation pathway distinguishes three decisions. First, the legal and procedural step requires an update of the existing IPPC discharge permit, alignment of the local urban wastewater management plan with Article 8, and registration of the indicator-substance monitoring programme under Articles 18–20. Second, financing may rely on the Extended Producer Responsibility (EPR) mechanism introduced by Article 9 of Directive (EU) 2024/3019, under which producers of pharmaceuticals and cosmetics are expected to cover at least 80% of the relevant costs of quaternary treatment, subject to national transposition. If an illustrative 20% public co-financing share is assumed for the CAPEX component, the remaining contribution for the 6.24 M€ O_3+BAF option would be approximately 1.25 M€. The final allocation of investment, operational and monitoring costs should, however, be defined after national transposition of the EPR mechanism.

The technical and economic assessment carried out for the Plovdiv WWTP shows that the requirements of the recast Urban Wastewater Directive for micropollutant removal can be achieved at competitive cost levels using ozonation followed by biologically active filtration (O_3+BAF) at

low to typical operating doses of 5–7 mg O_3/L, yielding total annual costs of 2.89–3.25 €/PE·y. Although stand-alone GAC shows a slightly lower nominal tabulated cost, this ranking is not decision-robust under current Bulgarian conditions because it depends on access to external reactivation infrastructure. The two PAC scenarios are flexible to deploy and CAPEX-light. However, the dominance of recurring reagent costs (706 – 1178 t PAC/y at 1.90 €/kg), together with a sludge increase of more than 10 % that may require stricter management - potentially including thermal treatment, depending on contaminant loading and final waste classification - places them in the most unfavourable position on the multi-criteria comparison.

The economies of scale of the Plovdiv WWTP further reduce the cost per equivalent inhabitant - the recommended O_3+BAF configuration places Plovdiv at 0.026 €/m^3 below the European economies-of-scale curve (Fig. 2), between WWTP-09 (195 000 PE, 0.08 €/m^3) and WWTP-10 (1 200 000 PE, 0.021 €/m^3), and below the overall average of the European reference set (7.3 €/PE·y). The recommendation is robust under the sensitivity envelope tested in Fig. 3, remaining below 4.16 €/PE·y under the one-at-a-time sensitivity tests applied to the four highest-leverage parameters.

A phased and flexible implementation is recommended, through the introduction of a technological scheme with ozonation at a minimum effective dose and biologically active filtration, supported by strict online monitoring ($UV_{(254)}$/DOC and bromate-BrO_3^-). The design of "modular" type facilities is an advantage to ensure smooth retrofitting with GAC when requirements are tightened or when a higher degree of removal is required. The final selection and settings should be validated through energy optimisation and a sludge management plan to achieve minimum overall costs and a sustainable environmental impact.

Use of Artificial Intelligence Tools

During the preparation of this manuscript, the author used Anthropic's Claude AI assistant to support language editing, improve readability, identify possible inconsistencies in terminology and presentation and the formatting of figures and tables from the author's own data and calculations. The technological dimensioning of the seven treatment scenarios, cost calculations and all numerical results were developed and validated by the author using self-developed engineering and financial spreadsheets. AI assistance is clearly distinguished from the data analysis and has not generated or created any technical content, design parameters, methodological conclusions or interpretations presented in this work. The author reviewed and revised the content independently and assumes full responsibility for the accuracy, originality and integrity of the work.

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References

Business Analytiq. (2025). Activated carbon prices [Price index]. https://businessanalytiq.com/procurementanalytics/index/activated-carbon-prices/

Council of the European Communities. (1991, May 21). Council Directive 91/271/EEC concerning urban waste water treatment (consolidated version 01.01.2014). Official Journal of the European Communities, L 135, 40-52. https://eur-lex.europa.eu

Donau Carbon GmbH. (2025). Reactivation of spent activated carbon. https://donau-carbon.com/Products-Solutions/Reaktivierung?lang=en-US

Elavarthi, B. R. (2021). GAC filter design criteria for wastewater treatment for removal of micropollutants (Master's thesis). Lund University Publication

EPA (2006). Wastewater Technology Fact Sheet: Ozone Disinfection. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-06/documents/ozon.pdf

European Commission. (1998, February 27). Commission Directive 98/15/EC amending Council Directive 91/271/EEC with respect to certain requirements established in Annex I thereof. Official Journal of the

European Communities, L 67 (7 March 1998), 29-30. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31998L0015

European Commission. (15 January 1999). Report from the Commission: Implementation of Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment, as amended by Commission Directive 98/15/EC of 27 February 1998-Summary of the measures implemented by the Member States and assessment of the information received pursuant to Articles 17 and 13 of the Directive (COM(1998) 775 final). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A51998DC0775

European Commission. (2019, December 13). Commission staff working document: Evaluation of Council Directive 91/271/EEC concerning urban waste-water treatment (SWD(2019) 700 final; Part 1/2). https://eur-lex.europa.eu/resource.html?uri=cellar:30d6b501-6cae-11ed-9887-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Commission. (2024). Directive

(EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment. https://eur-lex.europa.eu/eli/dir/2024/3019/oj/eng

Eurostat. (2025). Electricity prices for non-household consumers - bi-annual data (from 2007 onwards). European Commission. https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table?lang=en

IBEX - Independent Bulgarian Energy Exchange. (2025). Monthly bulletin: April 2025. Independent Bulgarian Energy Exchange EAD. https://ibex.bg/

Joller, N., & Hug, T. (2024, September 28). Evaluation of the energy and cost figures of processes for the elimination of micropollutants in wastewater treatment plants (Technical report No. 1490.26). Hunziker Betatech AG, for VSA Micropoll Platform. https://micropoll.ch/en/mediathek/evaluation-of-the-energy-and-cost-figures-of-processes-for-the-elimination-of-micropollutants-in-wastewater-treatment-plants/

Kommunalbetriebe Emmerich am Rhein. (2013/2014). Kläranlage Emmerich: 4. Reinigungsstufe zur Elimination von Mikroschadstoffen (Studie & Kurzbericht). Veröffentlicht über LANUV NRW. https://www.lanuk.nrw.de/fileadmin/tx_mmkresearchprojects/1217001_KA_Emmerich_4RS_01.pdf

LANUV NRW. (2021, May 31). Wegberg Wastewater Treatment Plant: Feasibility Study 4th Treatment Stage (as of 05/2021). State Office for Nature, Environment and Consumer Protection North Rhine-Westphalia. https://www.lanuk.nrw.de/fileadmin/forschung/21-05-31_699_1_Machbarkeitsstudie_Spurenstoffe_KA_Wegberg_FINALVERSION.pdf

LANUV NRW. (2022, May 12). Erkelenz-Mitte wastewater treatment plant: Feasibility study (final report). State Office for Nature, Environment and Consumer Protection North Rhine-Westphalia. https://www.lanuk.nrw.de/fileadmin/forschung/220512_Machbarkeitsstudie_KA_Erkelenz_Mitte_Abschlussbericht.pdf

LANUV NRW. (2020a, June 3). Feasibility study for the Eilendorf wastewater treatment plant (Final rev. 1). State Agency for Nature, Environment and Consumer Protection North Rhine-Westphalia. https://www.lanuk.nrw.de/fileadmin/forschung/2020_06_03_MS_Eilendorf-final_rev1.pdf

LANUV NRW. (2020b, June 23). Feasibility study on micro-pollutant elimination at the Krefeld wastewater treatment plant (long version and short version). State Office for Nature, Environment and Consumer Protection North Rhine-Westphalia. Long. https://www.lanuk.nrw.de/fileadmin/forschung/2020_MBS_Krefeld_Langfassung.pdf

Lugitsch & Partner ZT GmbH. (2022, August 3). Feasibility study 4. Treatment stage AWV Feldbach - Mittleres Raabtal (Final report). Office of the Styrian Provincial Government. https://www.wasserwirtschaft.steiermark.at/cms/dokumente/12889554_4570309/092438fa/Machbarkeitsstudie_Bericht_2022_08_03a.pdf

Margot, J., Kienle, C., Magnet, A., Weil, M., Rossi, L., de Alencastro, L. F., ... & Barry, D. A. (2013). Treatment of micropollutants in municipal wastewater: Ozone or powdered activated carbon? Science of the Total Environment, 461-462, 480-498. https://www.sciencedirect.com/science/article/abs/pii/S0048969713005779?via%3Dihub https://doi.org/10.1016/j.scitotenv.2013.05.034

Mulder, M., Poels, J., & Frijns, J. (2015). Costs of removal of micropollutants from municipal WWTP effluents (STOWA Report 2015-35).STOWA.https://www.stowa.nl/sites/default/files/assets/PROJECTEN/Projecten%202018/Stowa%20TAPES%20Final%20report.pdf

PDH-Pro. (2018). Wastewater design - Granular activated carbon systems (Course No. CH-02-905, 12 PDH). PDH-Pro LLC. https://www.pdh-pro.com/wp-content/uploads/2018/11/CH-02-905.pdf?utm

PFI Planungsgemeinschaft. (2019, June 24). Study on trace substance elimination at the Frechen wastewater treatment plant. Published via LANUV NRW. https://

www.lanuk.nrw.de/fileadmin/forschung/S2019-06-24_535-004_Spurenstoffelimination_KA_Frechen.pdf

Pistocchi, A., Andersen, H. R., Bertanza, G., Brander, A., Choubert, J. M., Cimbritz, M., Drewes, J. E., Koehler, C., Krampe, J., Launay, M., Nielsen, P. H., Obermaier, N., Stanev, S., & Thornberg, D. (2022). Treatment of micropollutants in wastewater: Balancing effectiveness, costs and implications. Science of the Total Environment, 850, 157593. https://www.sciencedirect.com/science/article/pii/S0048969722046915?via%3Dihub https://doi.org/10.1016/j.scitotenv.2022.157593

Sauter, D. (2024) The role of biological post-treatment following ozonation in advanced municipal wastewater treatment. RWTH Aachen University. https://publications.rwth-aachen.de/record/994980/files/994980.pdf

Stadt Ibbenbüren. (2019, July 8). Feasibility study on the further elimination of micropollutants at the Püsselbüren wastewater treatment plant (summary). https://www.lanuk.nrw.de/fileadmin/forschung/Ibb_Erläuterungsbericht_08_07_2019.pdf

Stapf, M., Miehe, U., Bester, K., & Lukas, M. (2020). Guideline for advanced API removal: CWPharma project report, GoA 3.4 - Optimisation and control of advanced treatment (Version 1, Project report). Zenodo. https://zenodo.org/records/4305935

Sturm, M., T., Myers, E., Schober, D., Thege, C., Korzin, A., & Schuhen, K. (2022). Adaptable process design as a key for sustainability upgrades in wastewater treatment: Comparative study on the removal of micropollutants by advanced oxidation and granular activated carbon processing at a German municipal wastewater treatment plant. Sustainability, 14(18), 11605. https://www.mdpi.com/2071-1050/14/18/11605 https://doi.org/10.3390/su141811605

TUTTAHS & MEYER Ingenieurgesellschaft mbH. (2019, October 22). Kläranlage Borken: 4. Reinigungsstufe zur Elimination von Mikroschadstoffen (Studie). Veröffentlicht über LANUV NRW. https://www.lanuk.nrw.de/fileadmin/forschung/191022_Borken_Studie_4_Stufe.pdf

U.S. Environmental Protection Agency. (2000). Wastewater technology fact sheet: Granular activated carbon adsorption and regeneration (EPA 832-F-00-017). https://nepis.epa.gov

VSA Micropoll Platform. (n.d.). Ozonation and post-treatment. Retrieved 7 June 2025 https://micropoll.ch/en/faq/ozonation-and-post-treatment/#:~:text=Yes%2C%20biological%20post,substances%20and%20their%20toxic%20effects

Wastewater treatment plant of the city of Niederkassel. (2020, October 28). Feasibility study on micro-pollutant elimination at the Niederkassel wastewater treatment plant. (Report published via LANUV NRW). https://www.lanuk.nrw.de/fileadmin/forschung/Abschlussbericht_Machbarkeitsstudie_Niederkassel.pdf

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