



# Energy, Economic, and Environmental (3-E) Analysis of Energy Recovery from Sewage Sludge in Municipal Wastewater Treatment Plants <sup>†</sup>

Dinko Đurđević <sup>1</sup>, Paolo Blečić <sup>2,\*</sup>, Igor Wolf <sup>2</sup> and Viktor Dragičević <sup>2</sup>

<sup>1</sup> Green Sustainable Solutions, Puškarićeva ulica 15, 10250 Stupnik, Croatia; d.durdevic@gssolutions.hr

<sup>2</sup> Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia; igor.wolf@uniri.hr (I.W.); viktor.dragicevic@uniri.hr (V.D.)

\* Correspondence: paolo.blecich@uniri.hr; Tel.: +385-51-651-543

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## Abstract

The article presents an energy, economic and environmental (3-E) analysis of a reference wastewater treatment plant (WWTP) with a capacity of 200,000 population equivalent (PE). The analysis includes sewage sludge treatment, anaerobic digestion (AD), combined heat and power (CHP), and mono-incineration of solar-dried sludge. The specific investment cost for the reference WWTP is 435 €/PE. Annual costs for operation and maintenance are estimated at 26 €/(PE·y) and the energy costs are 5 €/(PE·y). The annual energy demands are 32 kWh<sub>el</sub>/(PE·y) of electricity and 14 kWh<sub>th</sub>/(PE·y) of thermal energy for digesters' heating. For a specific sludge quantity of 20 kg<sub>DS</sub>/(PE·year), the biogas production is 245 Nm<sup>3</sup>/t<sub>DS</sub> or 5 m<sup>3</sup>/(PE·y). Biogas-driven CHP supplies 10.3 kWh/(PE·year) of electricity and 14.7 kWh/(PE·year) of thermal energy, which meets 30% of the electrical demand and 100% of the thermal energy demand. Total (capital and operation) costs of sludge mono-incineration are evaluated at 300 €/t<sub>DM</sub> or 6 €/PE. The heating value of digested and solar-dried sludge is 2 kWh/kg<sub>WM</sub>. The total cost of the solar drying system is 30 €/PE while the sludge solar drying rate is 370 kg<sub>DM</sub>/(m<sup>2</sup>·y). The environmental analysis showed that the on-site carbon footprint of the reference WWTP is 50 kg<sub>CO2eq</sub>/(PE·y), with the largest contributions arising from N<sub>2</sub>O emissions during wastewater treatment, CO<sub>2</sub> from sludge mono-incineration, and CO<sub>2</sub> from biogas combustion in the CHP unit.

**Keywords:** wastewater treatment; sewage sludge; triple-E performance; anaerobic digestion; sludge incineration; combined heat and power; carbon footprint



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## 1. Introduction

Municipal wastewater treatment plants (WWTPs) are essential urban facilities for protecting public health and water ecosystems [1], but at the same time they are also associated with substantial capital expenditure, operating costs, and strict environmental regulations [2]. Aside from wastewater treatment, WWTPs generate large amounts of sewage sludge, and managing this sludge is both energy- and cost-intensive [3]. Sewage sludge is increasingly being interpreted not just as a waste stream but also as a secondary resource containing recoverable energy, nutrients and material value [4,5]. This transition is particularly important in the European Union, where the revised urban wastewater framework places stronger emphasis on greenhouse gas reduction, circularity, and energy

autonomy [6]. Within this context, sludge-to-energy pathways are attracting scientific and practical interest [7]. Previous studies have shown that anaerobic digestion, combined heat and power (CHP) using biogas, thermal or solar drying, and mono-incineration, gasification, and pyrolysis can improve the energy and resource efficiency of WWTPs [8,9]. The overall performance of sludge treatment methods depend on the plant size, the sewage sludge properties, local energy prices, regulatory context, and the degree of process integration [10]. Recent research emphasizes that sludge treatment should be assessed through integrated energy, economic, and environmental criteria [11].

Rodríguez-García et al. [12] benchmarked 24 WWTPs across six typologies using life-cycle analysis (LCA) and showed that wastewater treatment methods affect the plant environmental and economic performance. Organic matter removal plants were found to be less costly in environmental and economic terms while more demanding reuse plants exhibited higher cost and environmental impact. Kamble et al. [13] evaluated the performance of WWTPs in India and identified electricity use, effluent emissions, and heavy metals as major contributors to the overall plant impact. Soil biotechnology achieved the lowest environmental impact while the aerated lagoons presented high electricity and chemical consumption. Abdallah et al. [14] compared septic tanks, conventional gravity sewers, and small-bore sewers using a cost-integrated life-cycle approach, finding that septic tanks were the least financially feasible, the conventional gravity sewers had the largest environmental footprint while small-bore sewers were the most favored in terms of overall economic and environmental performance. Campana et al. [15] studied the energy autonomy of WWTPs, optimizing PV, wind, storage, and treatment integration, finding that a renewable energy share of 70% achieved the lowest net present cost.

A considerable amount of research has also focused on sewage sludge reduction strategies. The quantity of sewage sludge generated in WWTPs can be reduced either within the wastewater treatment line or the sludge treatment line [16]. Strategies along the wastewater treatment line include techniques such as the use of chemical uncouplers [17], microbial predation [18], membrane bioreactors (MBRs) [19], and oxidation reduction systems with oxic-settling-anaerobic (OSA) processes [20]. Strategies along the sludge treatment line include thickening, anaerobic digestion, thermal hydrolysis, ozonation, ultrasound, wet oxidation, dewatering, thermal drying, and incineration [21–23]. Digestion and pretreatment reduce organic solids, while dewatering and drying reduce the water content and the transport volume.

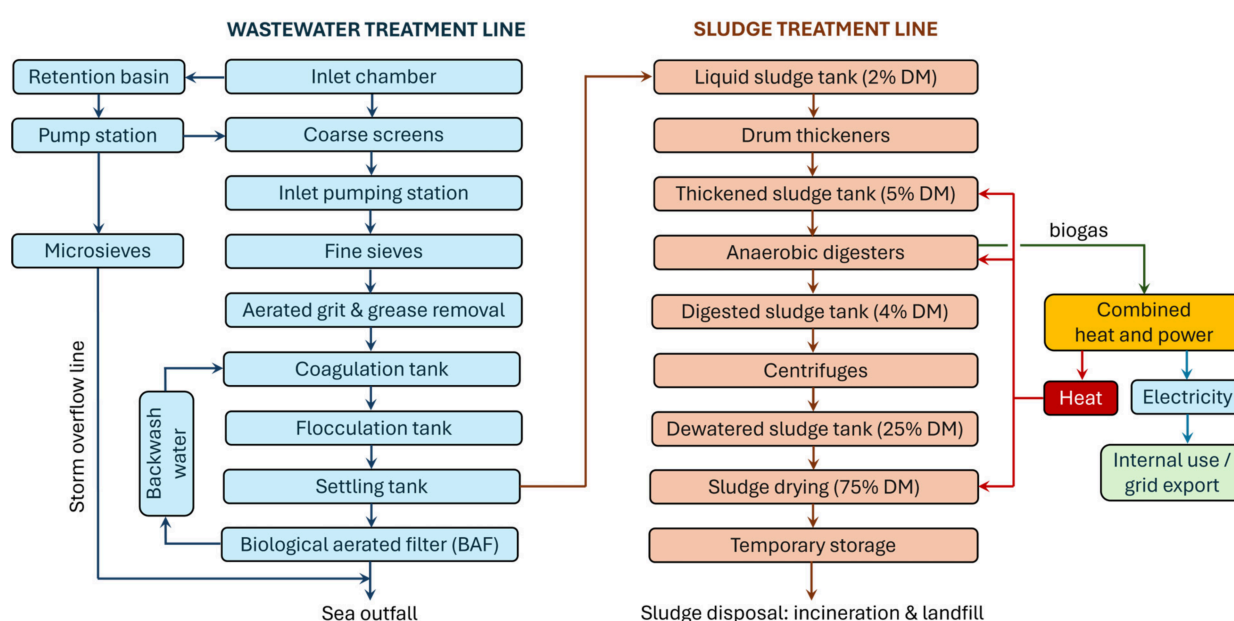
Although the literature contains extensive information on wastewater and sewage sludge treatment processes and their performance, fewer studies provide the 3-E evaluation of sewage sludge treatment methods with the investment and operational costs of WWTPs. Even fewer studies assess these aspects with the energy recovery potential, and the associated environmental impacts. The present study is motivated by the new WWTP under construction in Rijeka, Croatia, which will feature biogas production from anaerobic digestion along with sludge solar drying.

## 2. The WWTP Case Study

The new WWTP in Rijeka, Croatia, is planned as the central wastewater treatment facility for the city with a design capacity of 200,000 PE. The required effluent limits are 25 mg<sub>O2</sub>/L for the biological oxygen demand over 5 days (BOD<sub>5</sub>), 125 mg<sub>O2</sub>/L for the chemical oxygen demand (COD), and 35 mg<sub>DS</sub>/L for total suspended solids. The total (wastewater + infiltration) flow ranges from 42,400 m<sup>3</sup>/d in dry-weather up to 63,500 m<sup>3</sup>/d in wet-weather conditions. The average wastewater flow (infiltration excluded) is 32,650 m<sup>3</sup>/d [24].

The influent wastewater contains relatively high levels of municipal pollution. The influent design concentrations are: BOD5 285 mg/L, COD 635 mg/L, and suspended solids equal to 367 mg/L, total nitrogen 52 mg/L, and total phosphorus 9 mg/L. The corresponding daily pollutant loads are: BOD5 of 12,076 kg/d, COD of 26,918 kg/d, suspended solids equal to 15,542 kg/d, total nitrogen 2192 kg/d, and total phosphorus 380 kg/d [24].

The treatment train of WWTP Rijeka is shown in Figure 1 and consists of mechanical treatment, biological treatment, sludge treatment, and marine discharge through the existing submarine outfall. Mechanical treatment includes coarse screens, an inlet pumping station, fine screens, septage reception, an aerated grit and grease chamber, and lamella primary settling tanks. In the primary treatment stage, the plant uses ferric chloride ( $\text{FeCl}_3$ ) for coagulation and a polymer for flocculation, which improves solid capture, lowers the load sent to biological treatment, and reduces energy demand for aeration and mixing. The selected biological process is a biological aerated filter (BAF).



**Figure 1.** Wastewater and sewage sludge treatment lines of the studied WWTP.

Sewage sludge captured in the settling tank is first thickened and thereafter sent to the mesophilic anaerobic digesters. The planned WWTP Rijeka includes two anaerobic digesters, each with a volume of 3300 m<sup>3</sup>. Thickened sludge is stored in a 120 m<sup>3</sup> tank while the digested sludge is stored in another 120 m<sup>3</sup> tank. Centrifugal dewatering raises the dry matter content to 25%, after which thermal and solar drying will increase the dry matter content to 75%. In wet-weather conditions with heavy rainfall, the retention basin captures the first and most polluted runoff, allowing partial settling of suspended solids. The storm overflow activates only during intense rainfall, discharging mechanically clarified excess water into the sea, while the retained, more polluted fraction is subsequently pumped back to the main wastewater treatment line.

The biogas from anaerobic digestion runs an internal combustion engine for combined heat and power (CHP) generation to meet the energy needs of the WWTP. The recovered thermal energy is used for heating the anaerobic digesters, preheating the incoming thickened sludge and assisting sludge drying processes. The generated electricity is used to supply on-site electricity consumers or is exported to the grid. The sewage sludge production is estimated at 11 tonnes of dry matter per day, or 4000 tonnes per year (t/y). Other

residuals include 1400 t/y of screenings, 634 t/y of sand, 372 t/y of grease, and 50 t/y of septage reception [24].

### 3. Economic Analysis

#### 3.1. Specific Investment Cost

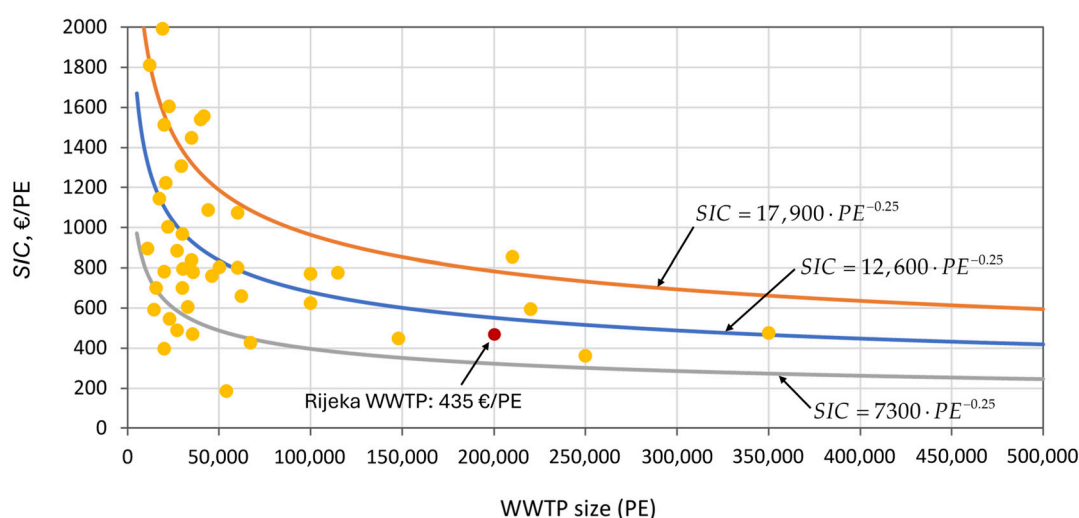
According to official sources, the main investment costs for the new Rijeka WWTP are €70 million VAT excluded or €87 million VAT included [25]. These costs include plant design, permitting, procurement, construction, testing, commissioning, staff training, and demonstration of operating costs during the trial operation. At a design capacity of 200,000 PE, the specific investment costs per population equivalent are 435 €/PE. A typical breakdown of capital expenditure for WWTPs is: civil construction 50%, mechanical equipment 20%, electrical and control systems 15%, engineering and design 10%, and site preparation 5% [25]. Economy-of-scale effects apply on WWTPs: as the plant capacity increases, the specific investment cost (SIC) in €/PE decreases, as determined by

$$SIC = SIC_0 \left( \frac{PE}{PE_0} \right)^n \cdot \frac{1}{PE} \quad (1)$$

In Equation (1),  $SIC_0$  and  $PE_0$  are the known costs and treatment capacity of a referent WWTP while  $n$  is the scaling exponent that describes the economy of scale and typically ranges from 0.60 to 0.80. Equation (1) can be reduced to the following form:

$$SIC = C_1 \cdot PE^{n-1}, \text{ where } C_1 = \frac{C_0}{PE_0^n} \quad (2)$$

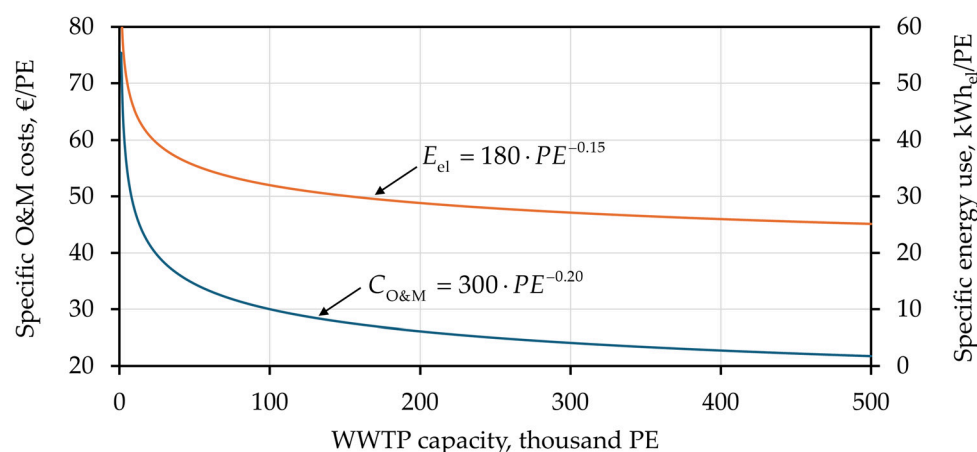
For new WWTPs in Croatia with secondary treatment, the analysis of the available data revealed that the cost scaling exponent is  $n = 0.75$  while the multiplying constant is on average  $C_1 = 12,600$ . The available data comes at high variance, and the standard deviation of the multiplying constant is  $\sigma_{C_1} = 5300$ . This means that 68% of WWTPs are expected to fall within the range of  $SIC = 7300\text{--}17,900 \cdot PE^{-0.25}$ , as shown in Figure 2. For Croatian WWTPs with secondary treatment, the average trend follows, which means that larger plants are generally more cost-efficient on a per capita basis. The planned Rijeka WWTP, at 200,000 PE and about €435/PE, lies within the expected cost range.



**Figure 2.** Specific investment costs (SICs) of Croatian WWTPs with secondary treatment.

### 3.2. Operation and Maintenance Cost

The operation and maintenance (O&M) costs of WWTPs vary with plant capacity, technologies involved, and wastewater and sludge treatment methods. An Austrian research report found median O&M costs of 20 €/PE·year for large WWTPs ( $\geq 100,000$  PE) [26], while official Austrian statistics report annual O&M costs of 21 €/PE·year for WWTPs  $> 100,000$  PE and 45 €/PE·year for WWTPs in the 5000–20,000 PE range [27]. For small activated sludge wastewater systems, the literature reports substantially higher O&M costs. For small plants, the average yearly O&M costs are 65–110 €/PE for WWTPs with 500 PE and 55–90 €/PE for WWTPs with 1000 PE [28]. All the above costs have been updated to 2025 price levels. Overall, these studies suggest that O&M costs for municipal WWTPs can range from around 20–30 €/PE·year for larger conventional plants to well above 50 €/PE·year for smaller facilities. This suggests that WWTP O&M costs exhibit economies of scale, similar to the specific investment cost (SIC), although data from real plants show substantial variability depending on plant size, configuration, and operating conditions. A tentative correlation between specific O&M costs and plant size is plotted in Figure 3, inspired by the correlation shown in [29]. This correlation estimates O&M costs at 26 €/PE·y for the Rijeka WWTP with 200,000 PE secondary treatment capacity.



**Figure 3.** Specific operation and maintenance (O&M) costs and specific energy use of WWTPs.

## 4. Energy Analysis

### 4.1. Energy Consumption

#### 4.1.1. Electricity Demand

The energy demand of WWTPs accounts for 10–30% of total O&M costs. The energy costs of WWTPs depend on plant size, wastewater properties and load, sewage sludge treatment methods, and energy recovery from biogas. Typical energy use range between 0.5 and 2.0 kWh/m<sup>3</sup> of treated wastewater, and the specific energy use is in the range of 20–45 kWh/PE for modern facilities [30,31]. A representative breakdown of electricity demand is 0.3–0.5 kWh/(PE·y) for screens, 1.7–2.2 kWh/(PE·y) for aerated grit chambers, 0.4–0.6 kWh/(PE·y) for primary sedimentation, 17.2–25.8 kWh/(PE·y) for aeration tanks, 1.2–2.3 kWh/(PE·y) for secondary sedimentation, 0.7–1.1 kWh/(PE·y) for sludge thickening, and 3.0–4.0 kWh/(PE·y) for sludge dewatering [29]. Excluding water pumping, the total electricity demand range is between 24.5 kWh/(PE·y) and 36.5 kWh/(PE·y).

In the EU-27, electricity prices for non-household consumers in 2025 were mostly in the range between 0.12 and 0.20 €/kWh. The EU-27 average electricity price for non-household consumers was 0.156 €/kWh, which is close to the average non-household electricity price in Croatia in 2025 (0.16 €/kWh) [32]. The corresponding WWTP energy costs, excluding wastewater pumping, are estimated at 3.82–5.69 €/PE·y when the average electricity price

is assumed, which corresponds to an energy cost share of 15–22% in total O&M costs. For the WWTP Rijeka, the specific electrical energy use is  $29 \text{ kWh}_{\text{el}}/(\text{PE}\cdot\text{y})$ , estimated from the correlation plotted in Figure 3. Thus, the specific cost of electricity is  $5.1 \text{ €}/(\text{PE}\cdot\text{y})$ , which represents 20% of the specific O&M costs.

#### 4.1.2. Thermal Energy Demand for Anaerobic Digestion

The thermal energy demand of the anaerobic digesters can be estimated from the annual sludge production of  $4000 \text{ t}_{\text{DM}}$ . Assuming thickened sludge with 5% dry matter (i.e.,  $50 \text{ kg}_{\text{DM}}/\text{m}^3$ ), the annual sludge flow to the digesters is  $80,000 \text{ m}^3/\text{y}$ , or  $219.2 \text{ m}^3/\text{day}$ . With a hydraulic retention time of 25 days, the required digester volume is  $5480 \text{ m}^3$ . Increasing the digester volume by 20% for the gas space, the total volume becomes  $6600 \text{ m}^3$ , or two digesters of  $3300 \text{ m}^3$  each. Based on the calculated digester surface ( $2 \times 1072 \text{ m}^2$ ), a heat transfer coefficient of  $0.5 \text{ W}/(\text{m}^2\text{K})$ , and an average year-round temperature difference of 25 K between the digesters and the ambient, the annual heat loss is estimated at  $235,000 \text{ kWh}/\text{year}$ , or  $1.2 \text{ kWh}/(\text{PE}\cdot\text{y})$  for a plant size of 200,000 PE. Even more thermal energy is required to heat the thickened sludge entering the anaerobic digesters. This thermal energy is calculated as  $2310 \text{ MWh}/\text{y}$  ( $11.6 \text{ kWh}/(\text{PE}\cdot\text{y})$ ), taking that the sludge flow quantity is  $80,000 \text{ m}^3/\text{y}$ , and assuming a sludge density of  $1050 \text{ kg}/\text{m}^3$ , a specific heat capacity of  $1.1 \text{ Wh}/(\text{kg}\cdot\text{K})$  and a temperature difference of 25 K between incoming stream and the digesters. The total specific thermal energy demand for anaerobic digestion is therefore  $12.8 \text{ kWh}/(\text{PE}\cdot\text{y})$ , and with an additional 10% allowance for auxiliary and distribution losses, the overall thermal energy requirement is approximately  $14 \text{ kWh}/(\text{PE}\cdot\text{y})$ .

#### 4.1.3. Thermal Energy Demand for Sludge Drying

Following anaerobic digestion and the breakdown of organic matter, the sludge quantity is assumed to decrease by 35%, from  $4000 \text{ t}_{\text{DM}}/\text{year}$  of raw sludge to  $2600 \text{ t}_{\text{DM}}/\text{year}$  of digested sludge. After centrifugal dewatering, the digested sludge has a dry matter content of 25%. Drying  $1 \text{ kg}_{\text{DM}}$  of sludge from a dry matter content of 25% to 75% requires the removal of 2.7 kg of water. The thermodynamic minimum thermal energy for the evaporation of 1 kg of water is  $2500 \text{ kJ}/\text{kg}_w$  or  $0.7 \text{ kWh}_{\text{th}}/\text{kg}_w$ . However, real drying systems operate with thermal energy demands close to  $q_w = 1 \text{ kWh}_{\text{th}}/\text{kg}_w$  [33]. Consequently, the specific thermal energy demand for sewage sludge thermal drying can be estimated from

$$q_{\text{drying}} = q_w \cdot \left( \frac{1}{\text{DM}_{\text{in}}} - \frac{1}{\text{DM}_{\text{out}}} \right) = 1 \frac{\text{kWh}_{\text{th}}}{\text{kg}_w} \cdot \left( \frac{1}{0.25} - \frac{1}{0.75} \right) \frac{\text{kg}_w}{\text{kg}_{\text{DM}}} = 2.7 \frac{\text{kWh}_{\text{th}}}{\text{kg}_{\text{DM}}} \quad (3)$$

Assuming that the specific sewage sludge load is  $20 \text{ kg}_{\text{DM}}/(\text{PE}\cdot\text{y})$  and that after anaerobic digestion this quantity is reduced to  $13 \text{ kg}_{\text{DM}}/(\text{PE}\cdot\text{y})$ , the thermal energy demand for sludge drying is  $35.1 \text{ kWh}_{\text{th}}/(\text{PE}\cdot\text{y})$ . If supplied by natural gas, this amount of thermal energy is equivalent to  $3.5 \text{ m}^3/(\text{PE}\cdot\text{y})$ . As an alternative, solar drying can be considered for new WWTPs. Assuming an average annual solar irradiation of  $1300 \text{ kWh}/(\text{m}^2\cdot\text{y})$  and a surface solar absorptivity of 0.80, the achievable evaporation rate is  $1000 \text{ kg}_w/(\text{m}^2\cdot\text{y})$ , assuming again  $1 \text{ kWh}_{\text{th}}/\text{kg}_w$ . This indicates that drying  $2600 \text{ t}_{\text{DM}}/\text{year}$  of digested sludge from 25% to 75% dry matter would require the removal of approximately  $7000 \text{ t}_w/\text{y}$ , which corresponds to a total solar drying area of  $7000 \text{ m}^2$ . On this basis, the specific solar drying capacity for sewage sludge is estimated at  $370 \text{ kg}_{\text{DM}}/(\text{m}^2\cdot\text{y})$ .

In solar drying systems, electricity is needed to power the air ventilation system and the sludge turning, mixing, and distributing device. The reported specific electricity consumption per tonne of evaporated water is 20–40  $\text{kWh}/\text{t}_w$  for natural ventilation while forced ventilation may increase the electricity consumption to 60–120  $\text{kWh}/\text{t}_w$ . A pilot-scale solar sludge drying system in Greece consumed  $83 \text{ kWh}/\text{t}_w$ , of which  $52 \text{ kWh}/\text{t}_w$  was used

by the exhaust ventilator and indoor mixing fans, while 31 kWh/ $t_w$  was used by the turning drum [34]. The authors also report a specific water evaporation rate of 1460 kg<sub>w</sub>/(m<sup>2</sup>·y) and a sludge drying rate of 390 kg<sub>DM</sub>/(m<sup>2</sup>·y). The specific installation costs were estimated at 24 €/PE [34], which updates into 32 €/PE in present-day prices. Thus, in the case of the Rijeka WWTP, the addition of solar drying would increase the specific electricity demand by 3 kWh<sub>el</sub>/(PE·y), raising the total specific electricity consumption to 32 kWh<sub>el</sub>/(PE·y).

In the summer, sewage sludge can be dried almost completely, reaching 90% dry matter content. On the other hand, in spring and autumn, partial drying is achieved, with dry matter contents ranging from 50% to 75%. In winter, low temperatures reduce the drying performance, and supplementary fossil fuel drying may be necessary.

#### 4.2. Energy Recovery

##### 4.2.1. Biogas from Anaerobic Digestion

For the Rijeka WWTP, with a design capacity of 200,000 PE, the annual sewage sludge production is estimated at 4000 t<sub>DM</sub>, corresponding to 55 g<sub>DM</sub>/(PE·day), or 20 kg<sub>DM</sub>/(PE·y). The sludge stabilization option is anaerobic digestion (AD) with a retention time of 25 days and an operating temperature of 38 °C. The sludge is assumed to contain 70% organic dry matter (ODM), of which 50% is biodegradable [35,36], resulting in an estimated dry matter reduction of 35% during digestion. Assuming a specific biogas yield of 0.7 m<sup>3</sup> per kg of dry organic matter reduced [37,38], the specific biogas production is 245 m<sup>3</sup>/t<sub>DM</sub>, equivalent to approximately 5 m<sup>3</sup>/(PE·y), obtained as  $0.7 \times (0.35 \times 4,000,000)/200,000$ .

The biogas properties and composition are summarized in Table 1, as reported in [34]. The biogas is utilized in a combined heat and power (CHP) unit. Assuming an average lower heating value of 6 kWh/m<sup>3</sup>, and a conversion efficiency of 35% for electricity and 50% for heat, the resulting specific outputs are 2.1 kWh<sub>el</sub>/m<sup>3</sup> and 3 kWh<sub>th</sub>/m<sup>3</sup>. For the annual sludge production of 4000 t<sub>DM</sub>, this corresponds to an annual energy generation of 2058 MWh<sub>el</sub>/y and 2940 MWh<sub>th</sub>/y. Expressed per one PE, the AD + CHP energy recovery unit could supply 10.3 kWh<sub>el</sub>/(PE·y) and 14.7 kWh<sub>th</sub>/(PE·y). Relative to the previously calculated energy demands of 32 kWh<sub>el</sub>/(PE·y) for electricity consumers and 14 kWh<sub>th</sub>/(PE·y) for anaerobic digester heating, the recovered energy from the AD + CHP could supply about 30% of the WWTP's electricity demand and enable full thermal self-sufficiency.

**Table 1.** Biogas properties and composition.

| Biogas properties                   |                           |
|-------------------------------------|---------------------------|
| lower heating value                 | 20–25 MJ/m <sup>3</sup>   |
| explosion limit in air              | 6–12%                     |
| self-ignition temperature           | 650–750 °C                |
| density                             | 1.0–1.2 kg/m <sup>3</sup> |
| Biogas composition                  |                           |
| methane (CH <sub>4</sub> )          | 55–70%                    |
| carbon dioxide (CO <sub>2</sub> )   | 30–45%                    |
| hydrogen sulfide (H <sub>2</sub> S) | 0.5–1.0%                  |
| ammonia (NH <sub>3</sub> )          | 0.05–0.10%                |
| water vapor (H <sub>2</sub> O)      | 1–5%                      |

##### 4.2.2. Thermal Energy from Sludge Incineration

With an annual sewage sludge quantity of 4000 t<sub>DM</sub>, and assuming that the sludge contains 70% organic dry matter (ODM), the initial ODM is 2800 t/y. If 50% of this organic fraction is degraded during anaerobic digestion, the degraded portion equals 1400 t/y. This

means that after anaerobic digestion, the remaining organic dry matter is 1400 t/y within a total dry matter quantity of 2600 t<sub>DM</sub>/y. Finally, this means that anaerobic digestion reduces the organic dry matter fraction from an initial value of 0.70 down to 0.538. The lower heating value of the digested sludge can be determined from the ODM and DM after anaerobic digestion and solar drying, using the empirical correlation from [39]

$$LHV_w = 21.7(\pm 0.56) \cdot ODM - 17.7(\pm 1.1) \cdot (1 - DM), \text{ MJ/kg}_{WM} \quad (4)$$

Using ODM = 0.538 and DM = 0.75 as inputs for the above correlation returns an LHV on a wet basis of 6.7–7.8 MJ/kg<sub>WM</sub>, corresponding to 2.0 kWh/kg<sub>WM</sub>, on average. Digested sludge typically achieves heating values lower than those of raw sludge; however, it can still be used in thermal recovery processes such as mono-incineration or co-combustion. The costs of sludge mono-incineration in Croatia are estimated between 200 and 400 €/t<sub>DM</sub>, depending on plant capacity, sludge composition and the resulting requirements for flue gases treatment, ash disposal costs, and local regulations. On average, the total (capital and operation) costs of sludge mono-incineration are estimated at 300 €/t<sub>DM</sub> or 6 €/PE, which is comparable to the costs found in Austria and Germany [40,41].

## 5. Environmental Analysis

The greenhouse gases emission expressed in tonnes of CO<sub>2</sub> equivalent are reported in Table 2. The specific electricity consumption is 32 kWh<sub>el</sub>/(PE·y) while the carbon intensity of the grid-mix electricity in Croatia is 109 g<sub>CO2</sub>/kWh<sub>el</sub> [42]. The methane slip is assumed as 100 g<sub>CH4</sub>/(PE·y), based on representative values within the reported ranges for the main sources of methane slip [43]: dissolved methane in wastewater (1–5 g<sub>CH4</sub>/PE·y), digester leaks (10–30 g<sub>CH4</sub>/PE·y), CHP unit leaks (5–20 g<sub>CH4</sub>/PE·y), and sewage sludge storage (10–100 g<sub>CH4</sub>/PE·y). Emissions from biogas combustion were calculated assuming a biogas composition of 60% CH<sub>4</sub> and 40% CO<sub>2</sub>, giving 1.97 kg<sub>CO2</sub>/m<sup>3</sup> of biogas. For sludge incineration, the carbon content in the digested sludge is assumed as 50% of the organic dry matter content, yielding 0.50 × 0.538 = 269 g<sub>C</sub>/kg<sub>DM</sub>, which converts into CO<sub>2</sub> according to the stoichiometric ratio 44/12 = 3.667 kg<sub>CO2</sub>/kg<sub>C</sub>. The emissions of N<sub>2</sub>O from wastewater treatment is 1.6% of total influent total nitrogen (2192 kg<sub>N</sub>/day), corresponding to an emission factor of 0.016 kg<sub>N2O</sub>/kg<sub>N</sub>, according to IPCC guidelines [44]. Finally, N<sub>2</sub>O emissions from sewage sludge incineration are assumed as 1.2 kg<sub>N2O</sub>/t<sub>DM</sub>, following IPCC guidelines for incineration of municipal solid waste and sewage sludge [45].

**Table 2.** Greenhouse gas emissions from WWTP Rijeka.

| Emission Category                         | Specific Value                           | Multiplier              | Carbon Equivalent                        | Emissions, t <sub>CO2eq</sub> /y |
|-------------------------------------------|------------------------------------------|-------------------------|------------------------------------------|----------------------------------|
| CO <sub>2</sub> —electricity consumption  | 32 kWh/PE                                | 200,000 PE              | 109 g <sub>CO2</sub> /kWh <sub>el</sub>  | 697.6                            |
| CH <sub>4</sub> —methane slip             | 100 g <sub>CH4</sub> /PE                 | 200,000 PE              | 28 kg <sub>CO2</sub> /kg <sub>CH4</sub>  | 560.0                            |
| CO <sub>2</sub> —biogas combustion in CHP | 245 m <sup>3</sup> /t <sub>DM</sub>      | 4000 t <sub>DM</sub> /y | 1.97 kg <sub>CO2</sub> /m <sup>3</sup>   | 1930.6                           |
| CO <sub>2</sub> —sludge incineration      | 269 g <sub>C</sub> /kg <sub>DM</sub>     | 2600 t <sub>DM</sub> /y | 3.667 kg <sub>CO2</sub> /kg <sub>C</sub> | 2564.7                           |
| N <sub>2</sub> O—wastewater treatment     | 0.016 kg <sub>N2O</sub> /kg <sub>N</sub> | 2192 kg <sub>N</sub> /d | 265 kg <sub>CO2</sub> /kg <sub>N2O</sub> | 3392.3                           |
| N <sub>2</sub> O—sludge incineration      | 1.2 kg <sub>N2O</sub> /t <sub>DM</sub>   | 2600 t <sub>DM</sub> /y | 265 kg <sub>CO2</sub> /kg <sub>N2O</sub> | 826.8                            |
| Total emissions                           |                                          |                         |                                          | 9972.0 t <sub>CO2eq</sub> /y     |
| Specific emissions                        |                                          |                         |                                          | 50 kg <sub>CO2eq</sub> /(PE·y)   |

The largest emission categories are N<sub>2</sub>O emissions from wastewater treatment (34%), sludge incineration (25.7%), and biogas combustion (19.4%), followed by N<sub>2</sub>O from sludge incineration (8.3%), indirect CO<sub>2</sub> emissions from grid electricity (7.0%) and unintentional methane slip (5.6%). The estimated total annual emissions is nearly 10,000 tonnes of

CO<sub>2</sub> equivalent, corresponding to a specific carbon footprint of 50 kgCO<sub>2eq</sub>/(PE·y). This value is consistent with those found in the literature. One study of Scandinavian WWTPs found carbon footprints in the range between 7 and 108 kgCO<sub>2eq</sub>/(PE·y) [46]. Another study determined that WWTPs in Greece operate, on average, with an on-site carbon footprint of 56.5 kgCO<sub>2eq</sub>/(PE·y) and an off-site carbon footprint of 16.9 kgCO<sub>2eq</sub>/(PE·y) [47]. In addition to greenhouse gases, the WWTP operation is associated with other air- and water-related pollutants. The main air-related pollutants are odor compounds such as hydrogen sulfide (H<sub>2</sub>S), ammonia, mercaptans, and amines. These are monitored at the air ventilation discharge. Water-related pollutants are monitored at the plant outlet and include wastewater pH, conductivity, dissolved oxygen, COD, BOD<sub>5</sub>, settleable solids and total suspended solids, total nitrogen, ammonia, phosphorus, orthophosphates, total fats and mineral oils, and anionic and cationic detergents.

## 6. Comparison with Other WWTP Case Studies

The performance of the Rijeka WWTP is comparable to other WWTP case studies found in the literature. The electricity demand of 32 kWh/(PE·y) corresponds to 0.54 kWh/m<sup>3</sup> when expressed relatively to the average wastewater flow of 60 m<sup>3</sup>/(PE·y). This value is equal to the average value found in large WWTPs in Greece, 32 kWh/(PE·y), but lower than the values found in small WWTPs, 48–137 kWh/(PE·y) [47]. It is also within the range of electricity demand of WWTPs in Poland, between 0.25 and 1.06 kWh/m<sup>3</sup> [48]. The Castiglione Torinese WWTP in Italy (2.7 million PE) reports an annual electricity demand of 24.7 kWh<sub>el</sub>/(PE·y) and a thermal energy demand of 18.2 kWh<sub>th</sub>/(PE·y) [49], while the thermal energy demand for the sludge line at the WWTP Rijeka is 14 kWh<sub>th</sub>/(PE·y). The electricity demand of the Rijeka WWTP is within the energy performance range of modern WWTPs and closer to larger and more energy efficient plants. In Rijeka, anaerobic digestion and CHP supplies 30% of the electricity demand and 100% of thermal energy. This is comparable to the values found in the literature. For instance, biogas-generated electricity typically supplies between 25 and 60% of the electricity demand in WWTPs [50].

The estimated 435 €/PE for Rijeka is consistent with the European range for medium-to-large secondary-treatment plants [11,25], while the projected O&M cost of 26 €/(PE·y) aligns with the Austrian benchmark of 20–21 €/(PE·y) reported by Haslinger et al. [26] and the official Austrian statistics for plants > 100,000 PE [27,41]. The estimated solar drying rate of 370 kg<sub>DM</sub>/(m<sup>2</sup>·y) is typical for the solar drying performance under Mediterranean climate conditions [34]. Specific installation costs of solar drying are estimated at 32 €/PE. Environmentally, the estimated carbon footprint of 50 kgCO<sub>2eq</sub>/(PE·y) is similar to the Greek average of 56.5 kgCO<sub>2eq</sub>/(PE·y) [47] and the 73–91 kgCO<sub>2eq</sub>/(PE·y) range that Ranieri et al. [51] reported for aerobic and anaerobic WWTPs in southern Italy. Marinelli et al. [52] also documented specific carbon footprints between 40 and 200 kgCO<sub>2eq</sub>/(PE·y) across 12 Italian plants of different sizes. The proposed integration of anaerobic digestion, combined heat and power, solar drying, and mono-incineration at the Rijeka WWTP produces a 3-E evaluation score that is competitive in the European contexts.

## 7. Conclusions

The energy, economic, and environmental (3-E) assessment of the new WWTP in Rijeka, Croatia, revealed that the specific investment costs are 435 €/PE while the energy demand is 32 kWh/(PE·y) of electricity and 14 kWh/(PE·y) of thermal energy. For an annual sewage sludge production of 4000 t<sub>DM</sub>, anaerobic digestion produces 245 m<sup>3</sup>/t<sub>DM</sub> of biogas, and the associated CHP supplies 10.3 kWh<sub>el</sub>/(PE·y) and 14.7 kWh<sub>th</sub>/(PE·y), which is sufficient to cover 30% of the plant electricity demand and the full thermal demand for digester heating. The environmental analysis showed an on-site carbon footprint of

50 kgCO<sub>2eq</sub>/(PE·y), with the dominant contributors being N<sub>2</sub>O emissions from wastewater treatment, CO<sub>2</sub> from sludge mono-incineration, and CO<sub>2</sub> from biogas combustion in the CHP unit. Future research could include off-site greenhouse gas emissions, alternative treatment methods for sewage sludge such as co-incineration, pyrolysis, gasification, and nutrient recovery. However, it should be noted that, as regulatory requirements tighten and sludge treatment moves towards more advanced energy and nutrient recovery technologies, WWTPs will be facing higher operating and compliance costs that could be transferred to final users through higher water supply and wastewater tariffs.

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## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                       |
|------|---------------------------------------|
| AD   | Anaerobic digestion                   |
| BAF  | Biological aerated filter             |
| BOD5 | Biochemical oxygen demand over 5 days |
| CHP  | Combined heat and power               |
| COD  | Chemical oxygen demand                |
| DM   | Dry matter                            |
| LCA  | Life-cycle analysis                   |
| LHV  | Lower heating value                   |
| O&M  | Operation and maintenance             |
| ODM  | Organic dry matter                    |
| PE   | Population equivalent                 |
| SIC  | Specific investment cost              |
| WM   | Wet matter                            |
| WWTP | Wastewater treatment plant            |

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